



Developing product families based on architectures

Contribution to a theory of product families

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Thesis for the degree of Doctor of Philosophy

Developing product families based on architectures

- Contribution to a theory of product families

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Abstract

The subject of this PhD thesis is development of product families based on architectures. Companies are introducing more and more product variants to fulfil the market demands. These new variants add complexity to many of the processes and systems in the companies. Re-use of *standard designs* (i.e. design entities) and re-use of the way new products are developed can simplify the processes and systems. Case studies show that re-use can lead to reduction of cost and time-to-market of new products.

One of the means for managing re-use of standard designs within product families are *architectures*. This research studies the phenomenon of product families that are developed based upon architectures. It is stated that an architecture describes the building principle of a product family and how the product family should evolve over time. This implies that an architecture should prescribe how standard designs are re-used in one or more products.

This research contributes with a vocabulary for product families. The vocabulary distinguishes among *architecture*, *platform*, *standard design* and *design unit*. The contribution is based on the artefact theories the Theory of technical systems and the Theory of domains. The vocabulary distinguishes between design entities, which are re-used (standard designs) and those that are not re-used (design units). Also, this research distinguishes between architecture and platform. An architecture is the building principle for product families. A platform is the physical and re-usable realisation of the architecture.

Two supporting tools are introduced in this research for modelling architectures and product families. The first tool is denoted *Generic organ diagram*. It aims at modelling the structures and interfaces of architectures. The second tool is denoted *Product family master plan* (PFMP). The PFMP aims at modelling product families and especially variety of product families.

The results of this thesis build on research literature and experiences from the industrial partners. Extensive verifications of the theory contributions, models and tools have been carried out in industrial projects. The primary industrial partner has been Bang & Olufsen, but other industrial applications have been carried out at Vestas, Alfa Laval, LEGO and YORK Refrigeration.

Keywords: product families, platforms, modules, standard designs and architectures

Resumé

Temaet for denne PhD afhandling er udvikling af produktfamilier baseret på arkitekturer. Mange virksomheder introducerer flere og flere produktvarianter i deres produktprogrammer for at tilfredsstille markederne. Disse nye produktvarianter tilføjer ekstra kompleksitet til virksomhedernes forretningsprocesser og systemer. Genbrug af *standard designs* (dvs. konstruktionsløsninger) og genbrug af måden hvorpå nye produkter fremtages, kan simplificere virksomhedernes forretningsprocesser og systemer. Studier viser at genbrug kan medføre reduktion i omkostninger og fremtagningstiden.

Et af midlerne til at håndtere genbrug af standard designs i produktfamilier er *arkitektur*. Dette forskningsprojekt har studeret hvorledes produktfamilier kan udvikles baseret på arkitekturer. Det fastslås at en arkitektur beskriver en produktfamilies byggeprincip, og måden hvorpå produktfamilien over tid skal udvikle sig. Det betyder at en arkitektur skal beskrive hvorledes standard designs genbruges i flere produkter.

Dette forskningsprojekt bidrager med et sprog som omfatter produktfamilier. Sproget skelner imellem *arkitektur*, *platform*, *standard design* og *design unit*. Det forskningsmæssige bidrag er baseret på Teorien for tekniske systemer og Domæneteorien. Sproget skelner mellem konstruktionsløsninger som kan genbruges (standard designs), og løsninger som ikke kan genbruges (design units). Endvidere skelnes der mellem arkitekturer og platforme. En arkitektur beskriver en produktfamilies byggeprincip, mens en platform beskriver den fysiske og genbrugelige del af arkitekturen.

To værktøjer introduceres til at modellere arkitekturer og produktfamilier. Det ene værktøj kaldes *Generic organ diagram*. Det anvendes til at modellere strukturer og grænseflader for arkitekturer. Det andet værktøj kaldes *Product family master plan* (PFMP). PFMP anvendes til at modellere produktfamilier og specielt variansen af produktfamilier.

Resultaterne af dette projekt bygger på litteraturstudier og erfaringer fra industrielle partnere. Omfattende verifikation af teoribidragene, modellerne og værktøjerne er gennemført i industrielle projekter. Den primære industrielle partner har været Bang & Olufsen, men andre industrielle projekter er gennemført hos Vestas, Alfa Laval, LEGO og YORK Refrigeration.

Stikord: produktfamilier, platforme, moduler, standard designs og arkitekturer

Preface

This PhD thesis documents a research project carried out at the Technical University of Denmark (DTU). The project has been carried out in collaboration between the Department of Mechanical Engineering at DTU and Bang & Olufsen.

The project was initiated January 2001 and ended March 2005. The project had duration of 36 months. The project has been interrupted for 12 months, while consultancy has been carried out for the Institute for Product Development at Vestas and YORK Refrigeration.

The work is primarily intended for researches in the area of engineering design. It is my hope that the readers from the engineering industry also will find the contents of this PhD thesis readable, interesting and applicable in their fields.

Many people have been involved in my PhD project and have contributed by means of insight, guidance and encouragement in the research process and the industrial applications. I would like to thank these people for their support.

First of all, I would like to thank my supervisor Associate Professor Niels Henrik Mortensen for invaluable guidance, commitment and inspiration throughout the project. Many hours in cars, trains or aeroplanes have provided opportunities for many discussions and exchange of ideas, which this research has benefited from.

Colleagues at the Technical University of Denmark and the Institute for Product Development (consultancy) provided an inspiring environment for this research. The members of the Product Architecture Group: Lars Hein, Mogens Myrup Andreassen, Sten Augsburg, Flemming Larsson, Rasmus Pedersen, Morten Kvist, Lone Munk and Ole Fiil-Nielsen have played an important role in creating this environment.

Additionally, I would like to express my gratitude to my industrial supervisors Ole Ploug, Jørgen Daucke and Allan Krogh Erlandsen at Bang & Olufsen for “opening the doors” to Bang & Olufsen and the many interesting projects. I also wish to thank my good colleagues at Bang & Olufsen, Vestas, Alfa Laval and LEGO for sharing their knowledge and experiences with development of product families.

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My family has played an important role in encouraging me to do the work, even though I have been away for long periods of time. Especially, my wife Tina deserves special thanks and love for her moral support, understanding and patience.

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Ulf Harlou
Copenhagen, April 2006

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Part 1

Setting the stage for developing product families based on architectures

The objective of this research project is to (1) enhance the knowledge of development of product families by means architectures, platforms, modules and standard designs. This research contributes (2) with models for product families based on architectures. The aim of Part 1 is to introduce the research problem, its objectives, the theoretical basis and how the research has been conducted.

1 Introduction to the research area

Companies strive continually to improve their business in order to please their customers, shareholders and other stakeholders. Such improvements relate to improvement of the organisations, processes, products, services, markets, etc. The improvements are carried out by different functional areas within the company. It is well known that improvements in the product development area can have high impact on a company's business. Empirical studies show that as the product concept is determined, approximately 70 to 80% of the manufacturing costs are disposed, EHRENSPIEL 1985. Similar rules seem to apply for other properties, e.g. quality, through put time, etc. Therefore, product development is not only about developing products, it is also about developing a company's business. Three of the dominant initiatives that companies implement in the product development organisations are: Lean Thinking, Six Sigma and Platform Development. These three philosophies strive to improve the companies' businesses and all three philosophies have impact on how product development is carried out.

Six Sigma is an American philosophy focusing on improving processes, e.g. development, manufacturing, use, service, etc. The Six Sigma methodology describes quantitatively, how a process is performing by means of statistics. The goal is to achieve Six Sigma, which

means that a given process must not produce more than 3.4 defects per million opportunities. A Six Sigma defect is defined as anything outside of customer specifications, BRUE 2003. General Electric is one of the successful companies that promotes this approach. General Electric estimates benefits on the order of \$10 billion during the first five years of implementation, SIXSIGMA 2004.

Lean Thinking is originally a manufacturing philosophy developed by Toyota. Lean Thinking emphasises to cut out the “fat” or waste in the manufacturing processes. Waste is defined as anything that does not add value to the customer. It could also be defined as anything the customer is unwilling to pay for. Seven types of waste are identified: Over-production, inventory, conveyance, correction, motion, processing and waiting. By eliminating waste, a company can do more with less: Less capital equipment, less floor space, less operator effort, less direct labour, less indirect labour, less inventory and less lead time, WOMACK & JONES 1996. Lean Thinking is also deployed in R&D departments under the name Lean Development, WARD 2002.

Platform Development means to develop subsystems that can be used in several products without or with minor modifications. This approach is known as an approach that significantly can reduce time-to-market. One of the companies that have introduced platform development with success is Volkswagen (VW). VW utilises platforms as a means for sharing a larger number of components across different car models. An example is their platform called “A”, which includes 60% of the components that are used in VW Golf, VW Bora, VW New Beetle, Audi A3, Audi TT and Skoda Octavia, KRUSCHWITZ ET AL. 2000.

The three approaches do not exclude each other. Many companies have applied several of the approaches at the same time with success.

Focusing on development of product families based on platforms and architectures

This research is in the line of platform development. The focus is development of product families and how platforms can be utilised for developing product families. The terms *product family*, *platform* and *architecture* are widely used in this thesis.

Definition of a product family

“A product family is a larger set of end products constructed from a much smaller set of components”, ULRICH & TUNG 1991.

Definition of a platform

“A platform is a set of common components, modules or parts from which a stream of derivative products can be efficiently created and launched”, MEYER & LEHNERD 1997.

One of the means to ensure re-use of platforms across products and product families is the so-called *architecture*. The architecture describes what components the platform consist of and how these elements can be combined into products.

Definition of an architecture

"I define product architecture more precisely as: (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specifications of the interfaces among interacting physical component." ULRICH 1995.

This research focuses on how the architectures enable re-use of components between product families. A thorough description of the above concepts is located in the chapter "Towards a vocabulary for architectures" (Page 77).

1.1 Response to business challenges: "The challenges of a growing product assortment"

The literature, conferences, news media, etc. reveal many success stories on companies applying platform development based on architectures. Many of the success stories have their origin in larger international companies like Volkswagen, Philips Consumer Electronics, Black & Decker, Hewlett-Packard, etc. In addition to the success stories, the literature also reveal that some companies find it challenging to handle all the variety within a product family, FRANKE ET AL. 2002.

As this research was launched, 12 Danish companies were visited in order to learn from their experiences with development of product families. Many of the companies reveal that in the past, it has been custom to develop individual products in independent projects. Focus has been on reducing cost and maintaining a high quality of the products. Consequently, there has been little re-use of solutions and parts from one project to another project. In case of re-use, it is typically driven by individual engineers or project leaders, who see re-use as a shortcut to make an engineering task quicker.

The following includes statements from R&D and project managers from the Danish companies. These managers all point out that developing individual products as independent projects is not an option in the future, because it will drain all R&D resources.

"If we continue doing product development the way we are doing it today, the entire department will be busy developing small variants for OEM customers"

Much focus is on customising existing products to key customers or OEM customers. Hopefully, this will satisfy the customers, but it also takes up a lot of the R&D resources and leave little time for being innovative and for developing new products.

"Most of our resources are spent on putting out fires"

A broad product assortment with many variants implies that maintaining these can be a big and challenging task. It takes time to develop solutions that can be implemented across a product assortment. Consequently, more and more time is spent on maintaining the existing product assortment.

"It will not be possible to launch the new products that are expected from our senior management"

As increasing resources are spent on customising and maintaining existing products, it is difficult to find the resources needed for launching new products in the rate expected from senior management and customers.

"The demand for growth cannot be fulfilled with our unstructured and undocumented product assortment and processes"

A growing product assortment demands that the product assortment is better documented in order to enable its maintenance. Also, if architectures, platforms and modules should be re-used from one product generation to the next, these must be documented in a more formal way than what is common in many companies.

"We have 20 years of experiences in not delivering on time and budget"

Not delivering on time possibly implies losing customers. Risk is a central issue for planning an introduction of new products. Too many unknown factors (e.g. new technologies) in a development project might increase the risk of not delivering on time.

The above statements are the outcome of a dialogue with the R&D managers and project leaders of 12 Danish companies. Their statements may not be considered statistically correct, but they do indicate that the Danish companies are facing a challenge - a challenge of growing product assortment that takes up more and more of the R&D resources in order to keep the assortment on the market. The consequence is too little time for being innovative and for developing new products. The experiences from the Danish companies are similar to what other companies have experienced, FRANKE ET AL. 2002.

There is a need for doing something different. There seems to be three categories of issues to address, if more resources are to be freed for developing new products:

- *Changing the product assortment and life phase system* – This means to change the product assortment or its life phase systems (production, service, transport, etc.) in such a way that the existing product assortment does not drain all available resources. Some of the means for this are modularisation, platform development and standardisation.
- *Introducing modern procedures* – Companies may choose to change the way that they work – work smarter hence more efficient. One of the means for this is to distinguish clearly between design preparation and design execution. Design preparation means e.g. developing platforms that later on can be implemented in several products. Design execution is to implement or integrate existing solutions in new products. The distinguishing between design preparation and design execution is in many ways similar to the distinguishing in the production area, i.e. production preparation vs. production execution.
- *Introducing IT systems* – Many companies have benefited from application of various IT systems (product models). These systems ease the handling of product data. Examples of these systems are Configuration Systems, Product Data Management (PDM) and Enterprise Resource Planning (ERP).

Experiences show that significant improvement of product development often requires that all three categories of issues are taken into account.

There seems to be a change in the industry from developing products in independent projects to development of product families. This change implies changes in the products and the processes, e.g. a higher degree of re-use of solutions. It also implies changes in the way development is carried out, i.e. distinguishing between design preparation and design execution. Finally, there seems to be a need for more IT systems to support the new kind of products (variance and re-use) and the new way of developing.

1.2 Response to an academic interest

Research in engineering design is dedicated to studying the development process from the initial idea to the start of production. The aim is to provide insight, tools, methods, theories, etc. into this field. In the past, the primary focus has been on development of single products. Many academics are aware of the trend in the industry – from development of a single product to development of product families.

Recently, increasing attention has been given to the phenomenon of developing product families and many publications on the topics have been published. These contributions aim to develop insight, tools, methods, theories, etc. which may improve business performance. The improvements affect different aspects of companies' businesses:

- *Offering more variants* – Authors like PINE 1999 focus on how to customise product to markets. This implies more product variants. The challenge for this approach is to offer many variants to markets with a high degree of re-use of components and processes.
- *Reducing time-to-market* – O'GRADY 1999 claims that architectures and modularity can lead to substantial benefits including reduction of product development times by 90 to 95%.
- *Improving the total business* – SANCHEZ & COLLINS 2001 argue that designing architectures are much more than a technical discipline. It can become a powerful management tools for identifying, developing, building and leveraging new competences. In other words SANCHEZ & COLLINS 2001 claim that architectures can be considered a strategic tool for improving products and business processes.

The phenomenon of developing product families is not new. The recent 10 years several research communities have contributed to this field. This research project rests on existing theories and insight.

1.3 Interpreting the needs

The conditions for product development change, when companies move from development of single products to development of product families and new needs arise. Architectures are one means to ease the challenges of developing product families, but the introduction of architectures also changes the conditions for product development.

Design preparation – The basic idea of an architecture is to have a larger set of subsystems that can be used in several products without or with minor modifications. Re-use implies that existing solutions are implemented into new products. The solution that is re-used should be prepared for future implementation – hence design preparation. Such design preparation often requires that the architecture includes features and interfaces that are not needed for the first implementation. However, these extra features and interfaces are needed in order to make the architecture suitable for future implementations.

Formalised documentation – If an architecture should be re-used, one should know what is re-used. One way of ensuring this is by means of formalised documentation of the architecture. Such documentation includes documentation of interfaces, functionality, performance, design guide lines for implementation, etc. Only few companies practise this discipline to the extent that is needed for development of product families based on architectures.

Change of responsibility – As an architecture is re-used there will be changes in responsibility.

ties. The engineer specifying, developing, implementing, maintaining, etc. might not be the same person. Such a shift in responsibility requires a high degree of knowledge transfer from one team to another.

Verification – Verification of a product family that includes thousands or even millions of variants can be an overwhelming task to perform. Verification of the individual products is not an option. New procedures, methods, tools, etc. are needed.

Coordination of projects – Re-use of subsystems and architectures across products and product families demand that the timing of the re-used elements is correct. A delayed or inadequate architecture may cause the product that is based upon this architecture will be delayed. The architecture must be aligned with products and technologies.

Portfolio management – Product families might consist of thousands or millions of product variants. It can be rather difficult to obtain an overview of all these variants – what goes into which product, what is the difference between the products, etc. It is especially difficult to obtain an overview of how the individual components can be combined.

The above changes are some of the changes that companies experience as they develop product families based on architectures. The scope of this research is not to solve all the above challenges, but to contribute with insight to the phenomena. This research primarily focuses on the phenomenon of architecture and the modelling aspect of product families as described in the following section.

1.4 Scope of this research

The scope of this research is based on two basic assumptions. The first assumption focuses on explicit and visual modelling:

Basic assumption on explicit and visual models

Explicit and visual models of product families enable better decision making regarding development of product families.

Development of product families is often considered a complex matter. The basic assumption in respect to this research is that decision making concerning product families can be enabled by means of explicit and visual models. Hereby, the “complexity” becomes manageable.

Existing products have virtues that the customers and other stakeholders appreciate. It is important to be aware of these virtues, when re-designing a product family or developing a new product family. On the other hand it is also important to be aware of the things that the customers and other stakeholders do not appreciate. There is no reason to repeat these in the new product family. In other words “*You should not be allowed to change anything unless you know what you are changing and the consequences it may have*”.

The implication of this assumption is that models, which visualise one or several aspects of a product family, enable better decision making concerning the product family. Hence, the results from this research will be a number of models and tools that in a graphical way present different aspects of product families. This assumption is very much inspired by the thinking pattern for the design process introduced by McKim 1972 at Stanford University.

Basic assumption on problem solving

Finding a solution to a problem is a heuristic step.

The second assumption is that finding a solution to a problem is a heuristic step, meaning that there is no direct link from a problem to a solution, FRANKE 1976. Consequently, it is not the goal of this research to formulate tools or methods that identify modules, architectures, platforms, etc. The objective of the models and tools are to visualise structures that put forward better decision making regarding development of the product families.

The two above assumptions together with the needs expressed by companies lead to the focus areas for this research. These are modelling of architectures and modelling of product families. The objective is to contribute to the following:

- *Enhance knowledge of product families based on architectures* – This research should enhance the knowledge and understanding of product families from an architecture point of view. This implies that this research should extend existing theories with new findings in this area.
- *Enhance knowledge of modelling product families* – Architecture is one aspect of dealing with product families. Another aspect is to obtain an overview of product families with thousands or millions of variants. There is a need for models that can provide an overview structure and variety of the product family.

2 Structure of thesis

This thesis is structured as follows:

Part 1 – Setting the stage for developing product families based on architectures

Chapter 1-5 present the framework of this research. It gives an introduction to the research problem, its objectives, how the research has been conducted and the theoretical basis.

Part 2 – State-of-the-art in developing product families

Part 2 is an investigation of the phenomenon “developing product families” based on a literature study. The aim is to clarify what is understood by developing product families and what is state-of-the-art in the industry (Chapter 7) and in the research theories on developing product families (Chapter 8). The state-of-the-art study is primarily based on literature.

Part 3 – Contribution to a theory of architectures for product families

With starting point in the Theory of technical system, the Theory of domains and the state-of-the-art study, Part 3 extends existing theories to include architectures for product families. Part 3 introduces a vocabulary for product families, which includes *architecture*, *platform*, *standard design* and *design unit*.

Part 4 – Supporting tools for developing architectures for product families

Part 4 introduces two tools, which can be applied for modelling architectures and product families. The first tool is denoted *Generic organ diagram*. It focuses on modelling the structures and interfaces of an architecture. The second tool is denoted *Product family master*

plan. It can be applied for modelling product families. It aims at modelling variety within a product family.

Part 5 – Industrial applications of architectures for product families

Chapter 17 illustrates how Bang & Olufsen have adapted the concept of architecture and standard designs. It also illustrates how they have benefited from application of the re-use of architectures and standard designs. It is estimated how they have reduced the R&D resources needed for developing new products and for maintaining the products by means of architectures and standard designs (Chapter 18). Finally, chapter 19 illustrates how Vestas has applied architecture for increasing parallelism in the development activities.

Part 6: Conclusions and future research

The results of this research and proposals for future research in this field are discussed in Part 6.

3 Scientific approach

This research belongs to the class of applied research in the field of engineering design. The PhD project has been carried out in collaboration between industrial companies (primarily Bang & Olufsen A/S) and the Technical University of Denmark (DTU), the Department of Mechanical Engineering. Collaboration between industrial companies and a technical university implies that this research has both theoretical and practical contributions within its scope, ROPOHL 1971. The theoretical goals aim at contributing to a theory by means of insight, definitions and axioms. The practical goals are to develop models that can be applied within companies.

3.1 Theoretical goals

Theories exist that describe what a product is, how it is developed and how to manage the development processes. However, theories describing product families and development of these are sparse. The theoretical goals of this research are to develop existing theories further and hereby extend them to be valid for product families based on architectures. The theories that are dealt with in this respect are the artefact theories Theory of technical systems and the Theory of domains.

The theoretical contributions are meant to enhance the knowledge of product families and enable formulation of models and methods for developing product families. The theoretical goals are:

- *Contribute to a theory of architectures for product families* – This research should enhance the knowledge and understanding of product families based on architectures. This implies that this research extends existing theories with new findings in this area.
- *Contribute to a theory for modelling product families* – This research should enhance the knowledge and understanding of modelling product families. A part of this contribution focuses on architectures. The contribution should also lead to enhanced knowledge of how to describe product families with thousands or millions of variants.

The theoretical contributions of this research are primarily formulated in connection with

formulation of models of the phenomena.

3.2 Practical goals

The practical goals of this research are to set up experiments within companies to get a better understanding of the phenomena of developing product families. The experiments along with the existing theories should also contribute to verifications of the postulated models and the extensions of the existing theories.

Involvement with industry and the experiments should hand over the findings to the industry. The goal is to develop a number of courses, which can hand over the insights, tools and methods that are developed throughout this research.

3.3 Hypotheses

Developing a product family differentiates from developing a single product in several ways, i.e. many variants, new working pattern, complex documentation, complex testing, etc. The hypothesis on architecture focuses on describing how the object (i.e. the product family) differentiates from a single product. The goal is to contribute to a theory of product families. The theoretical contribution should enable re-use of design solutions within product families by means of architectures and standard designs. Two hypotheses are formulated to fulfil this part of the research.

The first hypothesis aims at understanding the phenomenon of architecture, i.e. the building principle of a product family. The second hypothesis aims at understanding the elements of an architecture, i.e. standard design. Standard designs are design entities that are re-used within one or several product families.

Hypothesis no. 1 – Architecture

Hypothesis no. 1 states that a building principle for product families exists. This building principle is denoted *architecture*:

Hypothesis no. 1 – Architecture

It is possible to identify a model that is able to describe and document the building principle for individual products within a product family. This model, which is named "architecture", consists of the following elements: design units, standard designs, interfaces and application characteristics. Designing within such an architecture enables re-use of building principles and standard designs.

This hypothesis states that re-use of design entities (i.e. standard designs) is enabled by means of an architecture. The architecture describes the building principle by which the standard designs can be re-used within a product family. An architecture consists of design units, standard designs, interfaces and application characteristics (Figure 1).

Figure 1 illustrates the building blocks of an architecture. These are briefly described in the following:

- *Design units* – A product family can be divided into subsystems. These subsystems are denoted *design units*. Design units are design entities: Organs, parts, assemblies, mod-

ules, standard designs, etc. The standard design serves the purpose of encapsulating a part of a design into manageable units. Some of these units can be re-used in several products, others cannot.

- *Standard designs* – An architecture includes design units that are re-used across different products as well as design units that are not re-used. The design units that are standardised and used in more than one product are denoted *standard designs*.
- *Interfaces* – Besides design units and standard designs, an architecture includes interfaces. These interfaces connect the design units and the standard designs and enable these to function together. Another class of interfaces are those that connect the design units and the standard designs with the surroundings, e.g. input/output signals, power, external network, etc.
- *Application characteristics* – The application characteristics of an architecture describe what is relevant for the creation, implementation, documentation, maintenance, etc. of the architectures.

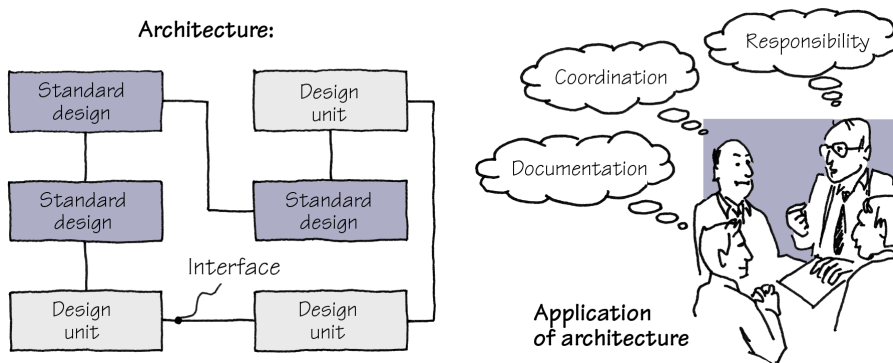


Figure 1. The building blocks of an architecture are design units, standard designs, interfaces and application characteristics.

Hypothesis no. 2 – Standard design

According to the first hypothesis, standard designs are essential constituent elements of an architecture. The second hypothesis deals with understanding what a standard design is.

Hypothesis no. 2 – Standard design

It is possible to describe re-usable solutions by means of three classes of characteristics - structural, functional and application characteristics. The re-usable solutions are denoted "standard designs". These three classes are necessary and sufficient for enabling re-use.

A standard design is an encapsulation of organs and/or parts into an entity that can be re-used in several products. A standard design is described by its *elements*, *functional properties* and the *application characteristics* (Figure 2).

A standard design is one of the key building blocks of an architecture. This research claims that a standard design consists of the elements shown in Figure 2, which are also described in the following:

- *Structural elements* – The structural elements of a standard design is the organs and/or parts. Organs and parts are described by the Theory of domains. In other words a standard design is an encapsulation of organs and/or parts that are used in more than one product.
- *Functional properties* – A standard design is a functional unit, meaning that it is able to deliver an effect. A power supply could be an example of a standard design that provides power, heating, noise, EMC noise, etc. As a standard design consists of organs, which has the functional properties of the organs. Standardisation of design units imply that functional properties of the products are standardised.
- *Application characteristics* – It is seldom that an R&D organisation re-uses standard designs automatically. Re-use of standard designs require new processes and organisational initiatives. The application characteristics of standard designs describe what is relevant for the creation, implementation, documentation, maintenance, etc. of the standard designs.

The two above hypotheses focus on formulating a contributing to a theory for developing product families based on architectures. Architectures should enable companies to re-use standard designs between product families.

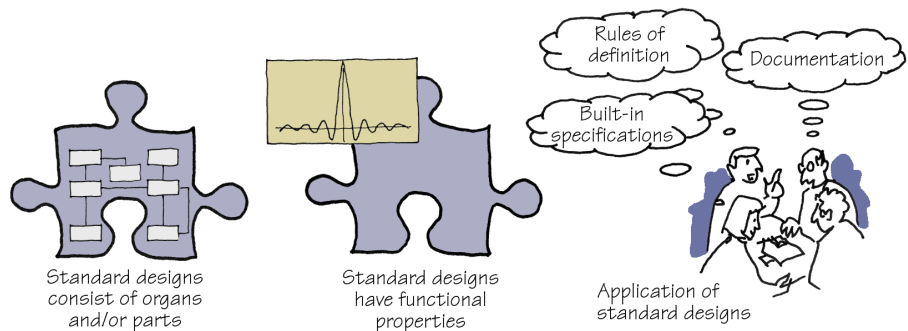


Figure 2. A standard design is a central part of the definition of an architecture. A standard design is described by its elements, functional properties and the application characteristics.

Delimitation

It is obvious that the change from development of single products to development of product families has an impact on many activities within the companies. Also, many theories need extensions to meet with the new challenges of variety. Figure 3 includes a model by ANDREASEN ET AL. 2001 that proposes some of the topics that are related to platform development and modularisation.

This research focuses on clarifying the artefact product families and how to model product families as outlined by the hypotheses. This implies that issues like organisation, management, design process, etc. will not be covered. However, when appropriate the issues are briefly covered.

Type of products – This PhD work focuses on development of product families for technical systems. As Bang & Olufsen is the main inspiration, the tools and theories should apply for mechatronic products. Mechatronic products are a synergy of mechanics, electronics and software design. Little focus is on software. This research will not contribute to new theories

in the field of electronics and software.

Type of businesses – Bang & Olufsen is well-known as manufacturer of consumer goods i.e. manufacturer of high-end audio and video products. The other companies that have been involved in this research cover a broad range of companies with very different types of businesses, e.g. mass production, one-of-kind, OEM driven, etc. This influences the results of this research in the sense that the results will be applicable for primary business within consumer goods. However, other types of industries will also be investigated in this research.

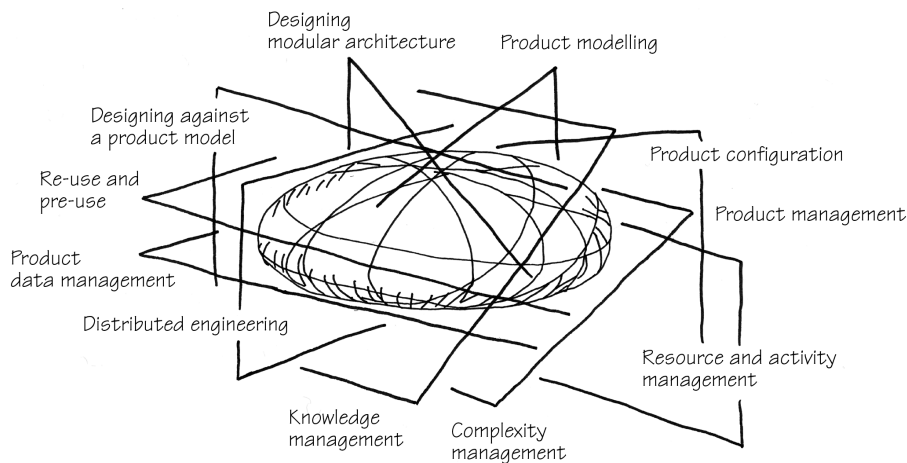


Figure 3. The “potato” of platforms and modularisation and the hereto linked “IT-structure” may be described by many cuts, ANDREASEN ET AL. 2001.

3.4 Research methods

The goal of this research is to contribute to, to improve and to understand the research phenomena “developing product families”. Such research is normally done by means of models of the design and the engineering process, HUBKA 1976, ROOZENBURG & EEKELS 1995.

According to JØRGENSEN 1992 research is both *problem based* and *theory based*, as so with this research project (Figure 4). The problem based research is a consequence of the participation in projects within companies and being in continuous dialogue with the companies. The theory based approach is due to the involvement at the university.

The problem based research is applied by means of an *action research* approach. Action research is based on researchers’ interest not only to observe, but to influence and control cases under research, HARMSSEN 1994.

The theory based research is applied by means of the *critical rationalism* approach. In critical rationalism, existing models and methods are improved to provide better descriptions of the empirical reality. This is done through literature studies, logical reasoning, empirical observations, etc. MØRUP 1993. Both the problem based and theory based paradigms are applied in this research.

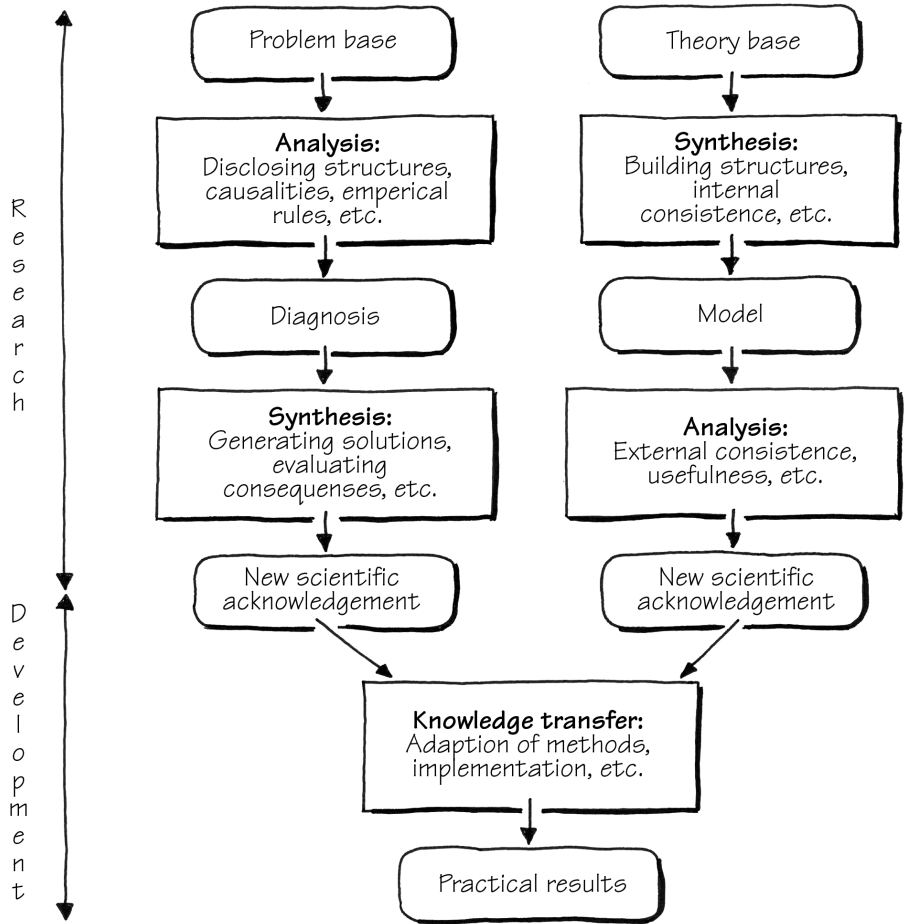


Figure 4. A method for applied research in which attention is focused on the interplay between theory and practice, JØRGENSEN 1992.

3.5 Research activities

This research is conducted through different kinds of activities: Literature studies, collaboration with research centres, conferences, research workshops, industrial workshops, experiments within companies and interviews with companies.

Literature

The literature studies have primarily been on product structuring, architecture modelling, platform development and modularisation. The artefact theories utilised in this research are the Theory of technical systems and the Theory of domains, but also the System theory (modelling theories) has played an important role in this work.

National and international research co-operation

Center for Industrial Production (CIP) at Aalborg University contributed in the early phase in the funding of this research project. Throughout the project informal research seminars

have been carried out with colleagues from CIP.

This research has benefited from study tours to other international research centres: Chalmers University of Technology (Gothenburg, Sweden) and University of Tampere (Finland).

Conferences and workshops

Participation at conferences and workshops has played an important role in this research. Some of the key conferences and workshops which have been attended in this PhD project, are:

- *Design 2004*, Croatia, Dubrovnik, 2004
- *Produktudviklingsdagen*, Denmark, Copenhagen, 2004
- *ICED'03*, Sweden, Stockholm, 2003
- *CIMdata PLM Conference*, USA, Detroit, 2003
- *Product Structuring and Modularisation*, Denmark, Copenhagen, 2003
- *Produktudviklingsdagen*, Denmark, Copenhagen 2003
- *NordDesign2002*, Norway, Trondheim, 2002
- *ELASM "Product Development Management Conference"*, France, Sophia Antipolis, 2002
- *Produktudviklingsdagen*, Denmark, Copenhagen, 2002
- *ICED'01*, Scotland, Glasgow, 2001
- *Produktudviklingsdagen*, Denmark, Copenhagen, 2001
- *NordDesign2000*, Denmark, Copenhagen, 2000
- *Produktudviklingsdagen*, Denmark, Copenhagen, 2000

A list of my publications is found in Appendix 1 (Page 173).

Teaching

Teaching within the universities – Results from this research have been taught in single lectures: Managers at the Master of Technology at Aalborg University ("Modularisation & Platform Development"), Master Thesis students at Norwegian University of Science and Technology ("Product Modelling" and "Modularisation & Platform Development") and Master Thesis students at Technical University of Denmark ("Design and Documentation"). A part of a PhD study is also to teach engineering students and to supervise Master Thesis students. The supervision has been carried out together with Niels Henrik Mortensen and Mogens Myrup Andreassen.

Teaching within the companies – Results from this research have been taught in 2-3 days courses in the industry: Bang & Olufsen ("Tools for Platform Development"), Alfa Laval ("Modelling Product Families"), LEGO ("Modelling Product Families"), Vestas ("Modelling Product Families"), YORK Refrigeration ("Modelling Product Families"), Danfoss Industrial

Controls ("Platform thinking patterns") and Federation of Danish Industries ("Tools for Modularisation and Platform Development").

Experiments at Bang & Olufsen

One third of the research activities have taken place at Bang & Olufsen by means of participation in different development projects (Table 1). The involvement in the projects varies from few weeks to up to six months. The participation in the different projects at Bang & Olufsen have contributed with insight into the phenomenon of developing product families. Also, the projects have served as objects for verification of the different models and tools. Bang & Olufsen has contributed to this research by means of project results (design contributions), tools and models.

Experiments within Swedish and Danish companies

Along with the research activities at the DTU and Bang & Olufsen, this research has also benefited from participation in projects in other companies (Table 2). These projects have been carried out in similar ways as the projects at Bang & Olufsen.

The participation in the different projects has all contributed to insight into the challenge of developing product families and many of the projects have served as objects to verification of the different tools. Throughout this thesis the above cases (Table 1 and Table 2) are used for illustrating different phenomena, tools and methods.

Interviews with companies

Several studies have been carried out at Philips Consumer Electronics (Eindhoven, the Netherlands) to learn how they have introduced and applied architectures and standard designs.

In the early stages of this research a number of interviews were carried out in the Danish industry. R&D and project managers from the following companies were interviewed: Danfoss Drives, Sauer-Danfoss, Radiometer, Aalborg Industries, Grundfos, Bang & Olufsen, Danfoss Instrumentation and Danfoss Building Controls.

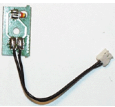


Project	Research focus	Product	
Standardisation of PCB. The PCB is re-used in 7 product families.	<ul style="list-style-type: none"> • Hypothesis no. 2 • Tool: Generic organ diagram 		NTC PCB
Cost/benefit analysis of development of platform for existing loudspeaker families. Development of family architecture.	<ul style="list-style-type: none"> • Hypothesis no. 1 • Tool: Generic organ diagram • Tool: PFMP 		BeoLab 2000, 2500, 3500, 4000, 6000 and 8000
Development of family architecture for new loudspeaker family.	<ul style="list-style-type: none"> • Hypothesis no. 1 • Tool: Generic organ diagram 		BeoLab 5
Development of strategy for digital TV architecture. Development of concept for family architecture for digital TV.	<ul style="list-style-type: none"> • Hypothesis no. 1 		Digital TV family architecture
Documentation of family architecture for audio portfolio.	<ul style="list-style-type: none"> • Hypothesis no. 1 • Tool: Generic organ diagram 		Audio family architecture
Documentation of standard design for TV scaler.	<ul style="list-style-type: none"> • Hypothesis no. 2 • Tool: Generic organ diagram • Tool: Standard design document 		TV scaler
Documentation of standard design for TV tuner.	<ul style="list-style-type: none"> • Hypothesis no. 2 • Tool: Generic organ diagram • Tool: Standard design document 		TV-tuner
Documentation of standard design for DVD.	<ul style="list-style-type: none"> • Hypothesis no. 2 • Tool: Generic organ diagram • Tool: Standard design document 		DVD

Table 1. Research activities which have taken place at Bang & Olufsen by means of participation in different development projects.










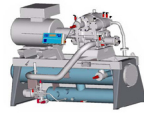
Project	Research focus	Product	
Alfa Laval: Standardisation of product family. Removing variety that does not add value to the customer.	<ul style="list-style-type: none"> Hypothesis no. 1 Tool: PFMP 		Heat exchanger (M10)
Alfa Laval: Documentation of product structure including variety and commonality.	<ul style="list-style-type: none"> Hypothesis no. 1 Tool: PFMP 		Control system for valves (ThinkTop)
Alfa Laval: Standardisation of product family. Removing variety that does not add value to the customer.	<ul style="list-style-type: none"> Hypothesis no. 1 Tool: PFMP 		Heat exchanger (CB50/51)
Alfa Laval: Documentation of a new modularised family of valves. The documentation forms basis for PDM, configuration and ERP structures.	<ul style="list-style-type: none"> Hypothesis no. 1 Tool: PFMP 		Single Seat Valves
Danfoss Drives: Documentation of family architecture for a new family of power frequency converters.	<ul style="list-style-type: none"> Hypothesis no. 1 Hypothesis no. 2 Tool: PFMP 		Power frequency converters
LEGO: Standardisation of mould parts that form the knobs of LEGO building blocks.	<ul style="list-style-type: none"> Hypothesis no. 2 Tool: PFMP 		Moulds
LEGO: Modularisation of moulds in order to bring down lead-time.	<ul style="list-style-type: none"> Hypothesis no. 1 Hypothesis no. 2 Tool: PFMP 		Moulds
LEGO: Analysis of new building blocks in 2001, 2002 and 2003. Basis for modularisation of moulds.	<ul style="list-style-type: none"> Hypothesis no. 1 		Moulds & building blocks
Vestas: Documentation of product structure and variety as basis for a simpler handling of variety within the ERP system (BOM).	<ul style="list-style-type: none"> Hypothesis no. 1 Tool: PFMP 		2 and 3 MW wind turbines
Vestas: Modularisation of new wind turbine. Specification of what modularisation should enable. Documentation of interfaces. Documentation of variety.	<ul style="list-style-type: none"> Hypothesis no. 1 Hypothesis no. 2 Tool: PFMP Tool: Generic organ diagram 		New wind turbine family
York: Restructuring of BOM for implementation in SAP (ERP).	<ul style="list-style-type: none"> Hypothesis no. 1 Tool: PFMP 		Screw compressors family SAB163

Table 2. Research activities which have taken place within companies by means of participation in different development projects at Swedish and Danish companies.

4 Theoretical basis

This chapter sets the theoretical basis for this research. The theories are related to understanding what a product is and how it is developed. The objective is to investigate theories and modelling formalism that form the theoretical basis. It should be possible to determine:

- What is the theoretical basis of this research?
- How can the theoretical basis contribute to this research?

The present chapter includes the key theories that are formulated at the Department of Mechanical Engineering (DTU), or theories to which the department has contributed. Later chapters investigate theories from other research groups (Part 2, page 41).

4.1 Theory of technical systems

A technical system refers to all types of human made artefacts. In the Theory of technical systems HUBKA & EDER 1988 have defined a technical process system. The technical process system is defined as consisting of four subsystems, a technical system (the product), a human system (the human operator), the environmental system (influence from the environment) and, finally, a technical process system (the meeting), Figure 5.

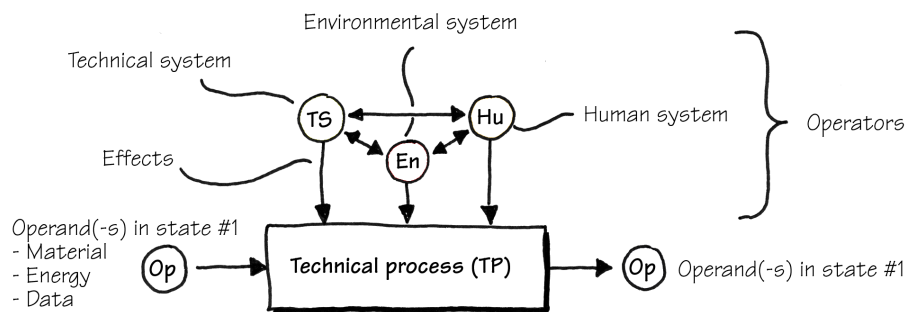


Figure 5. A technical process system consists of a technical process, an operand(-s), a technical system, an environment systems and a human system, HUBKA 1973.

In the technical process (also called transformation), one or more operands (Op) are transformed from an input state to an output state (the attributes of the operand are changed). An operand can be material, data or energy.

This process is enabled by one or more operators (TS, En, Hu) working together to deliver the effects that are necessary to execute the process. There is a sharp distinction between what the Technical System (TS) is and what the TS does. It is important to note that a desired process only can take place when there is the right interplay between the operands and the operators.

How the “Theory of technical systems” contributes to this research

The Theory of technical system forms the foundation of this research. Furthermore, this theory contributes to the key issues listed below:

- The operator (i.e. technical system (the product), a human system and the environmen-

tal system) can be designed, whereas the technical process cannot be designed.

- The technical process system is a basis for modelling how a product is a part of a technical process at a customer. In principle, as product families are developed, the product family should cover the variety of technical processes that the market needs.

4.2 Theory of domains

In the Theory of domains (ANDREASEN 1980), synthesis is explained as a gradual determination of structures in four different domains – a process, function organ and part domain. Each domain describes the product from a different viewpoint. A generic description of the product can be obtained by reading and modelling the four viewpoints.

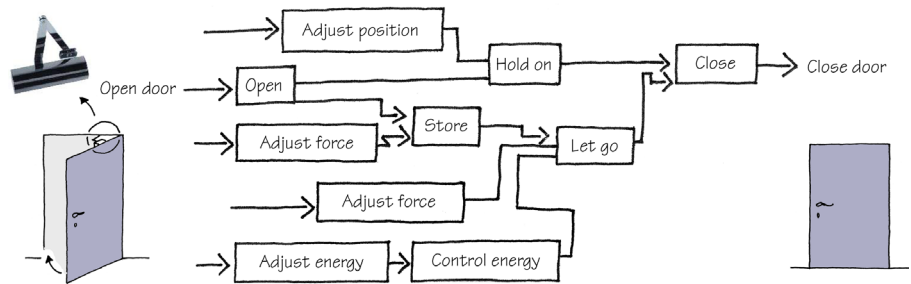


Figure 6. Process structure for a door opener mechanism, ANDREASEN ET AL. 1995A

Process domain – The modelling objects in the process domain are the transformations of material, data and energy that take place when the product is used (Figure 6). A process can be seen as being the same as the technical process in HUBKA 1973 technical process system, described in the previous section.

Function domain – In order for the process to take place, the product (i.e. the technical system), together with the other operators, need to deliver the necessary effects (Figure 7). These effects are created by the functionalities of the product. Thereby, the functions describe what the product must deliver.

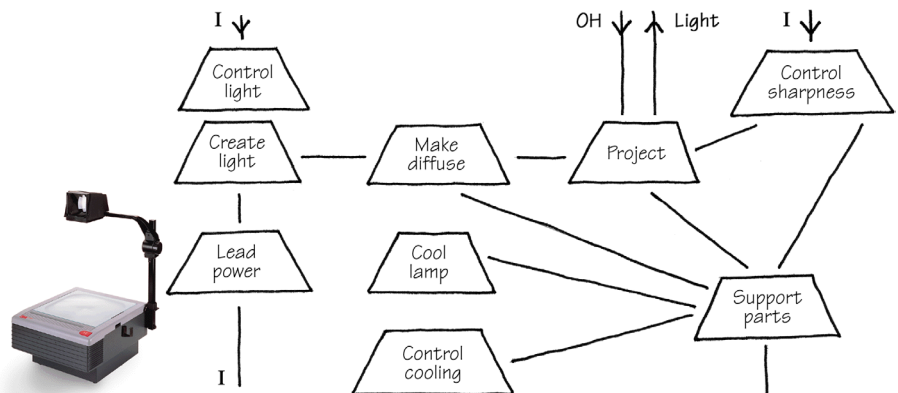


Figure 7. Function structure for an overhead projector, ANDREASEN ET AL. 1995A.

Organ domain – The organ domain describes the entities that create the effects and organs are sometimes referred to as function carriers. MORTENSEN 2000 defines an organ as a material element or an interaction between several material areas, which based on physical laws, can create effects, Figure 8. According to MORTENSEN 2000 the main reason for contemplating designs as organs is that functionality can be explained, which is not the case when individual machine parts are modelled.

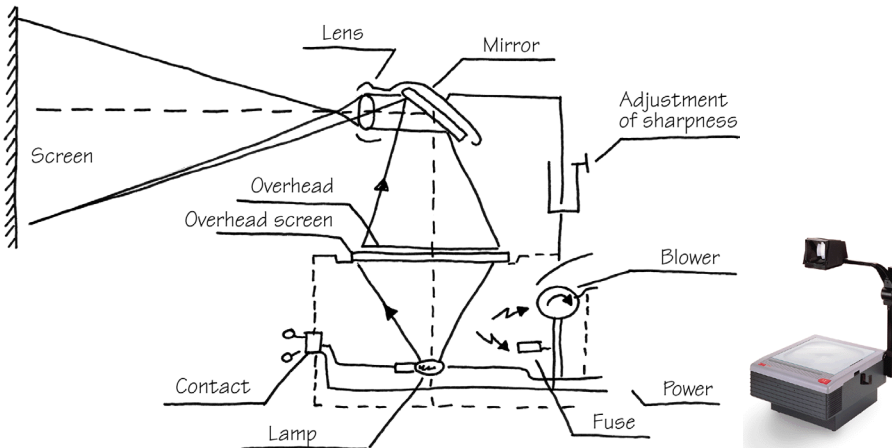


Figure 8. Organ structure for an overhead projector, ANDREASEN ET AL. 1995A.

Part domain – The physical realisation of organs is found in the part domain. By determining material, form, dimension, tolerance and surface quality of each part and the interrelation between parts, the necessary conditions for the organs and their functionality are created (ANDREASEN ET AL. 1996), Figure 9.

Coherence between the domains – A causal coherence between the domains exist, which can explain the interplay between the purpose of the product and the tasks realised by its parts. The purpose of the product, which is to create a purposeful output, is realised by its transformation process. The effects required to realise the process are created by the functions of the product. Its ability to create effects is connected to the organs. Finally, the organs are realised by the parts of the product and their couplings, ANDREASEN ET AL. 1996.

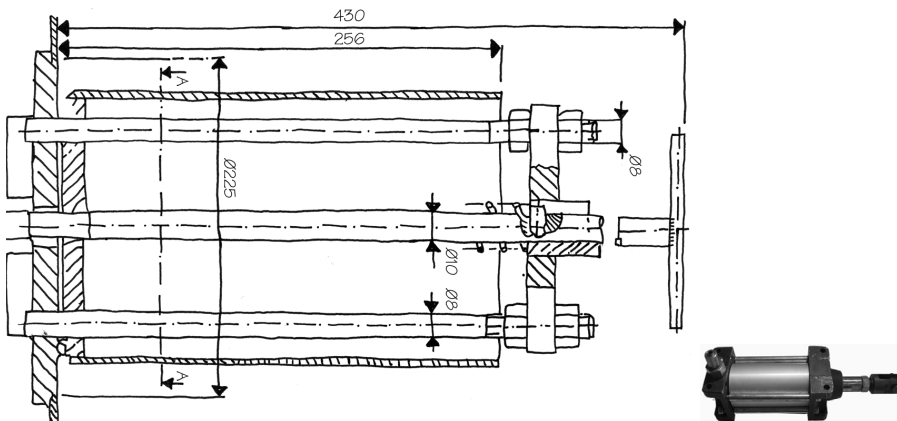


Figure 9. An example of a part structure, ANDREASEN ET AL. 1995A.

How the “Theory of domains” contributes to this research

The Theory of domains will in later chapters be applied for:

- The process domain is one way of describing how the customer applies the product. In later chapters the process domain is applied for describing the variety of applications that a product family has to fulfil in order to meet the variety of the markets.
- The organ and function domains form a basis for identification of standard designs that are similar. Such similarities form the basis for re-use of standard designs, modules and platforms.
- Re-use of single parts is related to the part domain.
- The coherence (i.e. leitmotif) between the four domains enables reasoning from purpose of the product to the physic realisation of the product. Chapter 15 shows that a such leitmotif for a product family will ease decision making about the necessary variety within a product family.

4.3 Multiple structures

The analysis and structuring of product related knowledge is often a very complex task, whether a product family is to be developed or modelled, e.g. in a commercial IT system. The ability to model a product family is sometimes referred to as the ability to “read” a product family.

In many companies the bill of materials are the predominant way to read a product and product family. The bill of materials is well suited for production, but is often inadequate for other functional areas, e.g. sales. The dilemma is that there is only one product or one product family, but many possible views or ways to “read” and structure the assortment, MORTENSEN & HANSEN 1999.

Often, when talking about the structure of a product we think of the physical part structure, but this is only one viewpoint. ANDREASEN ET AL. 1995^B state that “*the structure of a product is the way in which its elements are interrelated in a system model, based on the actual viewpoint*”. In other words the structure depends on the viewpoint and there are many superimposed structures – or viewpoints – to be found in the same product (Figure 10).

Product assortment views – A product is often a part of a product assortment. An overview of the assortment should show all the variants that are offered to the market and the commonality that exists between products and product families.

Product life views – The product life views relate to the life phase systems that the product will “meet” in its lifetime and the fitting of the product to these systems, e.g. production system, transportation system, etc.

Genetic product structure – These views belong to the Theory of domains, in which product synthesis is explained as a gradual definition of structures in four domains, ANDREASEN 1980.

Functional views – A product can be described by various property views like, control, thermodynamics, strength, etc. Models can be created for each of these views and specific domain languages define their structure.

How the “Multiple structures” contribute to this research

The ability to “read” a product family is important for modelling a product family, either for implementation in an IT system or as a basis for making decisions regarding the product family. The following key learning points have influenced this research:

- Architectures and standard designs can be defined in the generic “Product structure view”.
- Justification of the product structure is determined in the “Product life view”.
- Product variety and design re-use can be modelled mainly in the “Product assortment view”.

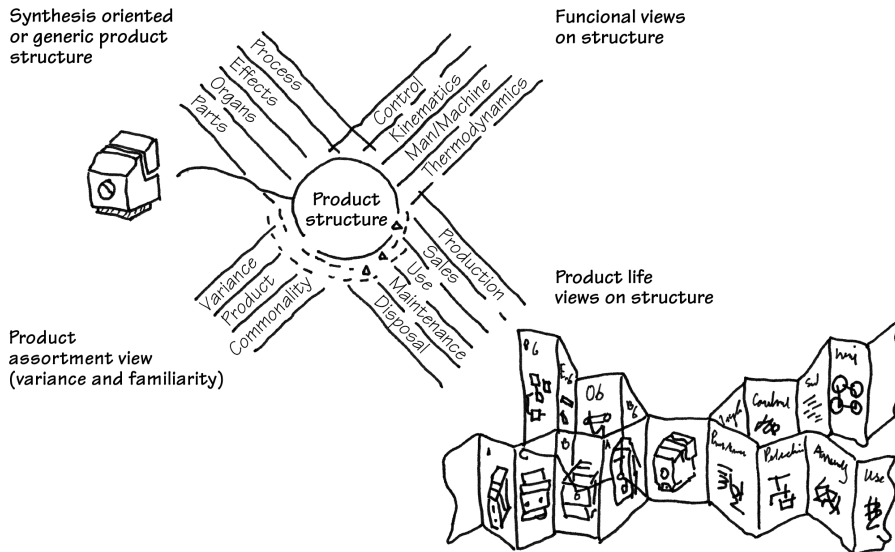


Figure 10. The totality of product structure views, showing four classes of structures of a product, ANDREASEN ET AL. 1996.

4.4 Genetic Design Model System

This next section deals with the so-called Genetic Design Model System (GDMS). The subject of the GDMS is synthesis of designs and product life, in interplay with a design support system, a “designer’s workbench”. The model system encompasses the design theory described in the previous sections, forming a comprehensive and coherent design model system consisting of four model classes: soll/ist, constitutive/behavioural, core/view and design/life phase system models.

Constitutive/behavioural models

In the GDMS there is a sharp distinction between attributes that define a design and attributes describing the behaviour of a design (The word “design” denotes the specifications of a product. A design is a result of a design process and a product is the result of a production process).

Attributes defining a design are called *characteristics* and they can be seen as answering the

question – What is it? I.e. the characteristics describe the constitution of the design.

The attributes describing the behaviour of a design are called *properties* and they can be seen as answering the question – What does it do? The properties are divided into *inherent properties* and *relational properties*.

Inherent properties are design attributes that are possessed by the design itself. Examples are strength, stiffness and weight. The inherent properties are causally determined based on the design characteristics and the environment.

Relational properties are design attributes, which describe the behaviour of the meetings between the design and the life phase system. Examples of relational properties are costs, throughput time and quality. Relational properties are causally determined based on the characteristics of the design, the life phase system and the meeting.

The main reason for a separation of constitutive and behavioural models is that the constitution (the characteristics) is the only thing that a designer can determine directly during design.

Soll/ist models

The behavioural models are further divided into *soll* and *ist* behaviour models (German for *should* and *is*). The *soll* behaviour models describe goals for behaviour and the *ist* behaviour models describe resulting behaviour, derived from the constitutive models.

Design/life phase system models

Yet, another dimension in the GDMS is the division between models describing the design and models describing the meeting between the design and a life phase systems. Figure 11 illustrates this division. The three “levels” in the so-called chromosome correspond to the transformation organ and part domains in the previously described Theory of domains. The fourth domain – the function domain – is not a part of the chromosome in the GDMS. The reason is that the chromosome is a constitutive model and functions belong to the behavioural model.

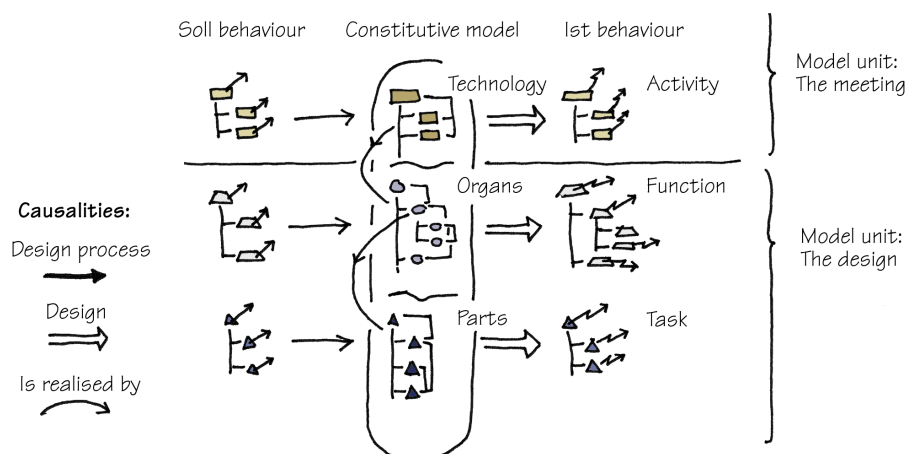


Figure 11. Constitutive and behavioural aspects of the chromosome model, MORTENSEN 2000.

The model object in the top part of the chromosome is the meeting between the design and the operand, the environment and the human system. A constitutive description of a meeting is designated *technology* (cf. the previously described *activity system*, HUBKA 1973). The soll and ist activity models describe the intended and realised transformation taking place in the meeting (denoted “Activity” in the Figure 11).

The design is modelled from two constitutive viewpoints – organs and parts. The two constitutive viewpoints are necessary for explaining the behaviour of a design and its physical realisation. The organ models describe the units that possess functions and the parts model describes the physical units that are realised in a sequence of production processes.

The part model can be seen as the core model in the chromosome. A part is constitutively defined by the design characteristics *material, form, dimension, tolerance* and *surface quality*. For part systems (part assemblies), the part *structure* defines the part system as an entirety. The soll and ist behaviour for parts is denoted *tasks*.

How the “Genetic Design Model System” contributes to this research

The main aspect related to the Genetic Design Model System (GDMS) is the clear distinction between constitutive and behavioural models. This is relevant when defining the constitutive and behavioural parts of an architecture or a standard design.

4.5 Theory of dispositions

During its lifetime a product will go through a sequence of “meetings”, OLESEN 1992. A meeting is whenever a product takes part in an action where the product, an operator and a life phase system are interacting (Figure 12).

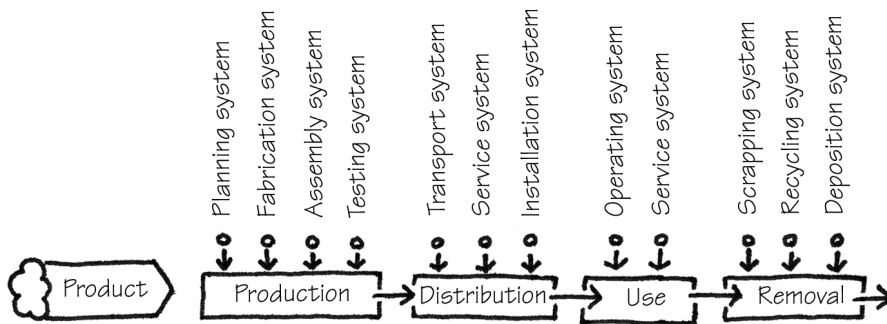


Figure 12. During a product's lifecycle the product goes through a number of meetings, OLESEN 1992.

The meetings are interesting because it is only in the meetings that the performance of a product can be evaluated – a product by itself has no performance. OLESEN 1992 proposes that this performance can be evaluated along seven dimensions – the so-called *seven universal virtues*: cost, time, quality, flexibility, efficiency, risk and environmental effects. A consequence is that in order to achieve the optimal performance, the product must be fitted to these life phase systems and/or vice versa.

A life-phase model also serves the purpose of elucidating the consequences of design decisions. OLESEN 1992 proposes the Theory of dispositions. “By a disposition we understand the part of a decision made within one functional area that affects the type, content, efficient or

progress of activities within other functional areas”, OLESEN 1992.

OLESEN 1992 introduces the score model (in Danish: Partiturmodel), which illustrates that as the product is designed many other systems are also designed or disposed for (Figure 13). For instance, decisions on the size of a TV influence the type of transportation that is possible for transporting the TV from the local dealer to the final customer. It is worth noticing that such a decision is made long before the actual transportation takes place – hence *disposition*.

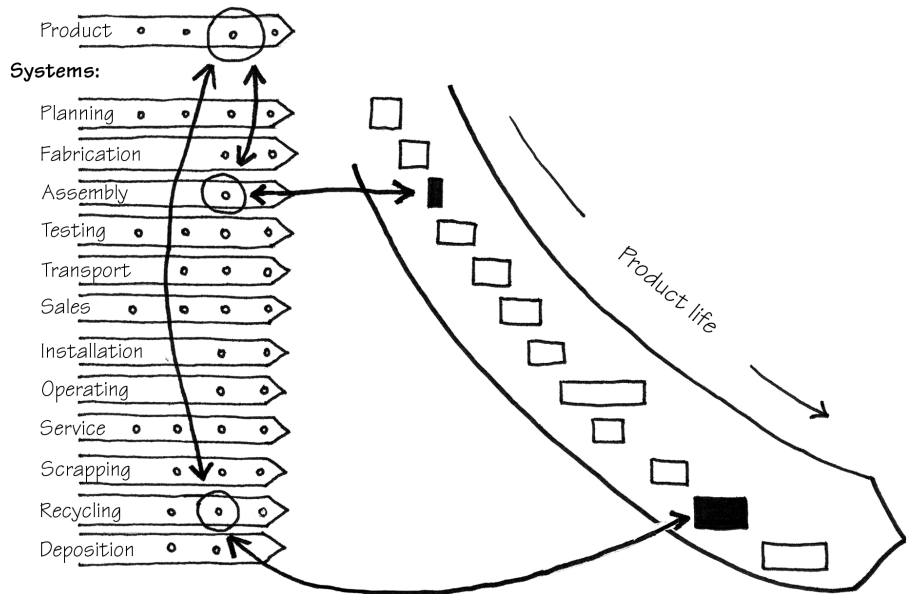


Figure 13. A score model, which gives an overview of all the systems that the dispositions affect when a product is developed, OLESEN 1992.

How the “Theory of dispositions” contributes to this research

The Theory of dispositions is related to architectures and standard designs, because architectures and standard designs are applied to achieve an advantageous effect in a life phase. The key lessons learned from this theory are:

- The mechanism of dispositions is important to understand when standard designs and platforms are developed, as these are often introduced in order to achieve an effect in later life phase systems, e.g. simple test, simple assembly, etc.
- The totality of a product’s performance is the sum of the performance of the product in all of its life phase systems.

4.6 Theory of design processes

According to ANDREASEN & HEIN 1987 the development process can be described in terms of single models on four levels: product planning, product development, product synthesis and problem solving. Figure 14 illustrates the relationship between the four types of models. The design process theory is based on descriptive and prescriptive models from HUBKA 1976, PAHL & BEITZ 1986 and HANSEN 1974.

Product planning – Product planning is related to activities where decisions regarding introduction of new products and phasing out existing products are made. Product planning also involves initiation and stopping of development projects.

Product development – Product development comprises the activities, which together create the business. The model proposes interplay among three classes of activities. Activities related to market, product and production. This model is also known as the *Integrated Product Development*, ANDREASEN & HEIN 1987.

Product synthesis – TJALVE 1989 suggests a model for synthesis of products. The model has its starting point in decomposition of the functions of the products. Hereafter, solutions are found by means of principle and quantified structures.

Problem solving – The model for general problem solving comprises the steps which lead to the solution of a problem. The model is applicable for many types of problem solving.

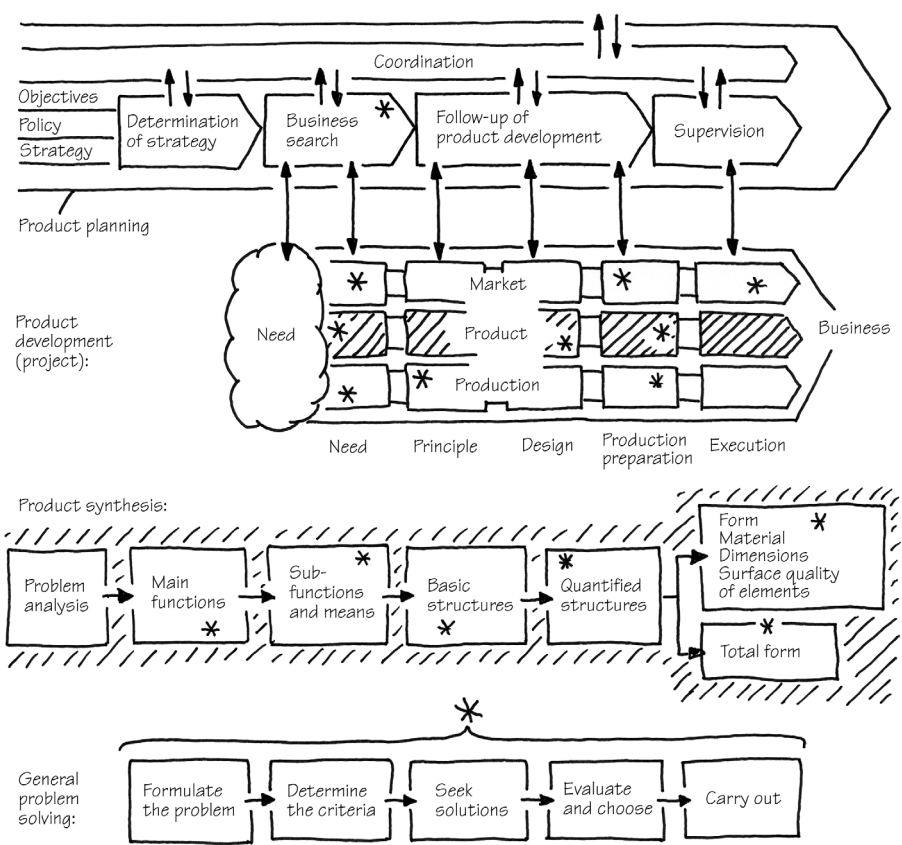


Figure 14. Four levels of models for the design processes, ANDREASEN & HEIN 1987.

How the “Theory of design processes” contributes to this research

The Theory of design processes is the framework of developing processes that forms basis for this research. As the Theory of design processes is formulated by ANDREASEN & HEIN 1987 it does not cope with product families. However, later on we will learn that developing prod-

uct families involves development activities on all four levels. In the following, focus is on tools that primarily support product planning and product synthesis.

4.7 Conclusions on a theoretical basis

The four theories Theory of technical systems, Theory of domains, GDMS and Multiple structures form the understanding of what a product is for this research. The above theories are all valid for single products. The theory of Multiple structures introduces a view for modelling product families, but is not extensive. One of the tasks for this research is to extend these theories to be valid for product families.

The Theory of dispositions and the Theory of design processes are all needed to understand the context within which product families are developed.

The theories introduced in the above are all considered as a necessary foundation for research at the Department of Mechanical Engineering, the Technical University of Denmark. The following chapters include other theories that are related to developing product families, i.e. platforms, architectures and standard designs.

5 Conclusion on setting the stage

Part 1 of this thesis sets the stage for this research, meaning that the reader should understand the motivation, activities and goals for this research. The main conclusions from Part 1 are that there seems to be a change in the industry. Companies are changing from development of single products to development of product families. This change introduces new challenges in the industry. Also, the existing theories do not cope with development of product families.

The scope is to enhance the knowledge of product families and to contribute with tools that visualise how architectures and standard designs are re-used. This research is based on a set of theories that primarily are dedicated to development of single products. Part 2 investigates the phenomena of developing product families further.

Part 2

State-of-the-art in developing product families

The objective of Part 2 is to explore what companies and researchers have done in the field of developing product families. The sources of input are industrial cases and theories. The state-of-the-art study clarifies how this research can benefit from other authors' contributions and how this research can contribute to existing theories and findings.

The main purpose of Part 2 is to obtain an overview of existing theories and contributions to theories related to the development of product families. Other researches have worked with the phenomenon of developing product families and their main contributions are outlined in the following. Also, industry has contributed with new insight and approaches for developing product families. Part 2 provides answers to the following:

- What main theories describe development of product families?
- How do companies handle development of product families?
- How can the insight from academia and industry contribute to this research?
- What is missing?

The goal is not to provide exhaustive descriptions of all theories and tools, but to provide an overview of state-of-the-art in research and industry in relation to the development of product families. This overview forms the base for introducing models, tools and theoretical contributions in later chapters.

Structure of Part 2 – This part initially looks into a number of industrial cases to investigate how companies deal with developing product families. Hereafter, literature is studied to give an overview of theories that cope with the phenomenon. Part 2 concludes by classifying the contributions from other authors and companies and by stating the key learning points from literature. The state-of-the-art study is used in later chapters for highlighting how this research contributes to the research communities.

6 Framework for investigating the phenomenon of developing product families

Developing product families is a multifaceted object to study and not all issues are addressed in this research. Figure 15 includes an overview of some of the key topics addressed in literature.

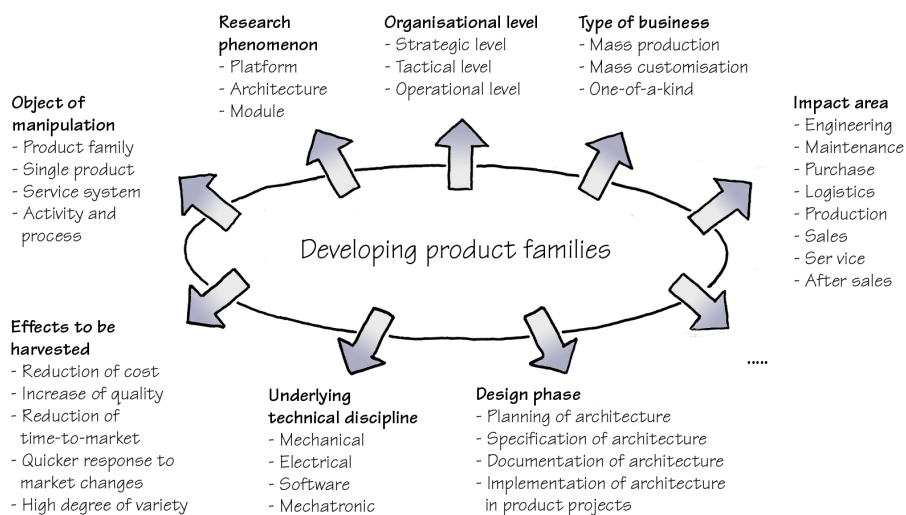


Figure 15. Many aspects are relevant for development of product families. This figure includes classes of topics related to development of product families found in literature.

The topics of Figure 15 are described in the following:

Object of manipulation – The primary object to manipulate when developing product families is, obviously, the *product family*. Another object of manipulation is the individual products – hence *single product*. Several of the existing theories and tools applied for developing product families have their origin in development of single products. Initiatives are also done in the production, service and other areas (*service system*). Re-use of standard designs, modules and platforms are also applicable for a service system, e.g. re-use of production equipment. Architectures and modules are often considered isolated, but the most successful projects also include standardisation of *activities and processes* related to product family.

Research phenomenon – The academia terms related to the development of product families are platform, module and architecture. Numerous definitions of these terms exist. For the purpose of studying state-of-the-art a *platform* is a group of subsystems that are used

in one or several product families. A *module* is a subsystem designed for re-use. An *architecture* describes the structure of the product and the interfaces of the modules and platforms. A more thorough description of these terms is introduced in “Towards a vocabulary for architectures” (Page 77).

Effects to be harvested – Developing one product family with a high degree of re-use can be reasoned in many ways. Some of the dominant reasons are *reduction of cost, increase of quality, reduction of time-to-market, quicker response to market changes, high degree of variety*, etc.

Impact areas – Development of product families based on architectures can have great impact on the entire business. Consequently, one or more functional areas will be influenced by the initiatives. Example of impact areas are: *Engineering, maintenance, purchase, logistic, production, sales, service, after sales*, etc.

Organisational – Different academia focus differently on how to apply architecture development and modularisation in companies. Some focus on the *strategic* aspects, other on *tactical* aspects. Finally, some focus on the *operational* level. In general, the strategic and tactical approaches focus on changing the business and the organisation, whereas those who focus on the operational level primarily focus on the development of tools and methods for developing product families.

Design phase – Different authors focus differently depending on where in the design phase they focus, i.e. *planning, specification, development, documentation and implementation of architecture*.

Underlying technical discipline – The underlying technical disciplines vary from author to author. The four major classes are *mechanical, electrical, software* and *mechatronic*. Mechatronic products are synergies of mechanics, electronics and software design. Within this research, only limited studies have been conducted in the area of software.

Type of industry – Different industries have different priorities. Development of product families in companies that practise *mass production, mass customisation* (OEM) and *one-of-a-kind* are different.

The following chapter investigates state-of-the-art in developing product families. Part 2 concludes by classifying authors’ contributions on the topic of developing product families (Page 70).

7 State-of-the-art: Studies on development of product families in industry

Companies experiencing the challenges of developing product families find ways to handle these challenges regardless of whether the phenomenon is described by theories or not. The following aims at presenting some of the insights that are provided by companies:

- How have companies benefited from architectures, platforms and modules when developing product families?
- What thinking patterns have the companies applied?

The aim of this chapter is not to provide a total overview of how companies work with prod-

uct families. That is, unfortunately, not possible, because companies are often reluctant with publishing that kind of knowledge due to confidentiality. The sources for this chapter are literature studies and visits at companies.

7.1 Case: VW

Literature on platform and architecture development often refers to Volkswagen (VW) as one of the success stories in this field. However, little literature comes directly from VW. The following case study is based primarily on sources KRUSCHWITZ ET AL. 2000, PIECH 2000, PIECH 2001, EICHORN 2001 and PISCHETSRIEDER 2002.

VW introduced platform development as a means to launch more product variants to the market and at the same time to standardise the components (platforms). One of the platforms is called "A", which VW Golf, VW Bora, VW New Beetle, Audi A3, Audi TT, Skoda Octavia, etc. are based on (Figure 16).

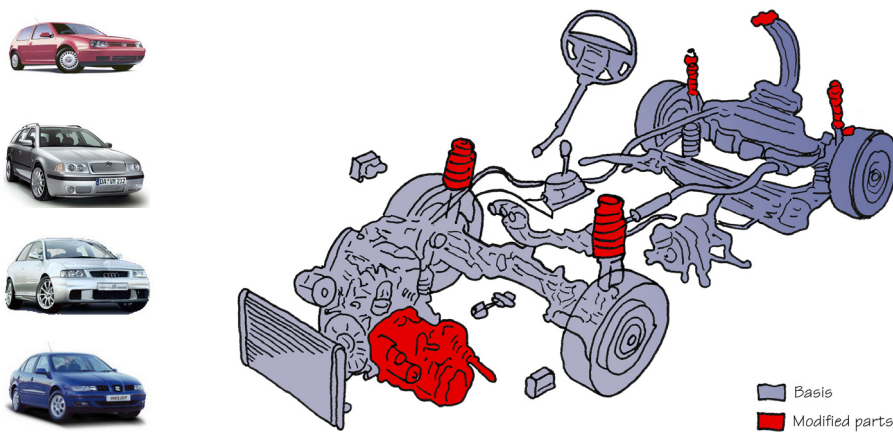


Figure 16. Power train, which is included in VW Golf, VW Bora, VW New Beetle, Audi A3, Audi TT, Skoda Octavia, etc. EICHORN 2001.

According to VW *"The platform is an entity that has no impact on the vehicle's outer skin ... A platform can be completed to obtain various independent models by adding so-called "bodies". The bodies comprise the parts which the customer can see and feel"* KRUSCHWITZ ET AL. 2000. In other words, a platform consists of components that the customer cannot see. Their platforms comprise the front axle, steering and steering column, gearshift mechanism, pedal cluster, rear axle, brake system, fuel tank, exhaust system, wheel, front end, bulkhead centre floor, rear end, seat frame, wiring and electrics, KRUSCHWITZ ET AL. 2000. These elements are re-used in several product families, i.e. VW Golf, VW Bora, etc.

In order to ensure that the customers conceive the various products differently, it is emphasised where the "look and feel" of differentiation is located (VW term: "bodies"). Figure 16 includes an example of the power train. The parts that are coloured red in Figure 16 are those that contain the differentiated driving properties. The rest of the power train is identical in VW Golf, VW Bora, VW New Beetle, Audi A3, Audi TT, Skoda Octavia, etc.

According to KRUSCHWITZ ET AL. 2000, about 60% of the components comprising the volume of a car model belong to the platform and about 40% to the "body" (Figure 17). This implies

that 60% of the components are re-used between the different car models. VW has also experienced other positive effects from introduction of platforms, KRUSCHWITZ ET AL. 2000:

- Innovations can be transferred to new models at a faster pace.
- Reduction of variety of components has dropped by 80% due to re-use of components.
- Other brands can introduce new models in short time.
- Reduction of cost, due to higher volume of parts.
- Reduction in investment, due to a lower degree of variety in production.
- Production is more flexible, due to a lower degree of variety in production.
- Higher quality by pooling experiences.
- The number of components to be developed and support has been reduced drastically.

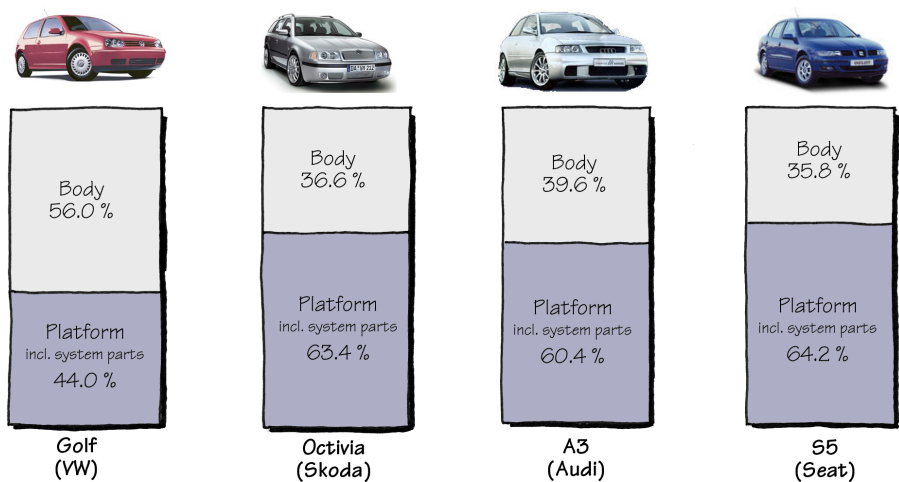


Figure 17. About 60% of the components comprising the volume of a car model belong to the platform and about 40% to the body, KRUSCHWITZ ET AL. 2000.

How VW contributes to this research

The VW case shows the benefits from application of platforms and architectures. The key learning points from this case are:

- Cost benefits can be achieved through application of platforms.
- Free R&D capacity can be achieved through application of platforms.
- Identification of what is common for all products forms basis for identification of platforms. VW has not standardised components that are carriers of “the look and feel” of the car.

Even though VW shows great results from their application of platforms, the case shows little on how to apply platform thinking and little on the nature of platform thinking. The aspects related to architecture and standard design are not treated in the present publications on VW. Literature does not reveal how VW carries out the development of the platforms. Nei-

ther does literature reveal any negative consequences from platform application.

The VW case is included in this research to outline the benefits that can be achieved through application of platforms and to illustrate key thinking patterns behind platforms, e.g. standardisation of subsystems that do not meet the customers' eyes.

7.2 Case: Sony HandyCam

Sony has like VW applied an approach, where a high degree of re-use within a product family has been achieved. This case is based on PALLMAR 2001 and SANCHEZ 1999b. The case has been presented by Ron Sanchez and Modular Management, respectively.

Sony launched a family of video cameras with the name "HandyCam". This product family consists of the modules illustrated in Figure 18. The blue blocks in the top row of Figure 18 illustrate the modules of the first generation of the HandyCam family. It is told that Sony was the first on the market with this type of small handheld video cameras. By being the first on the market, Sony had the advantages of getting a relatively good share of the market.

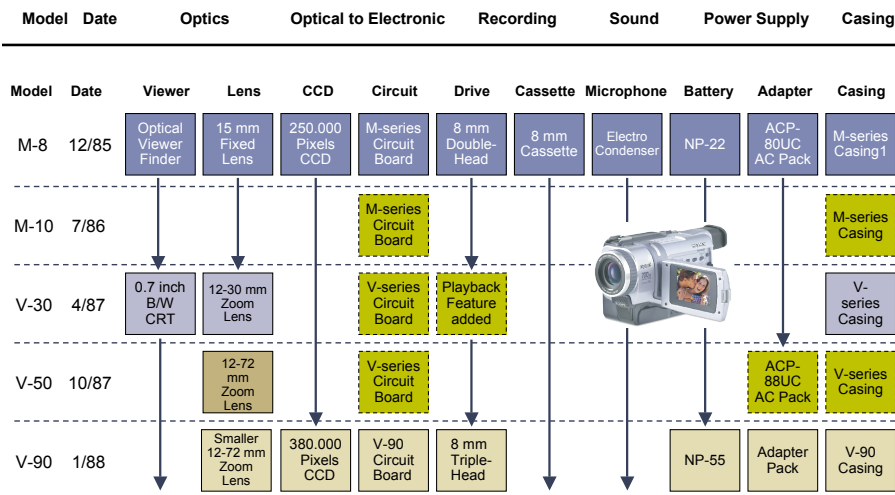


Figure 18. Illustration of the modules within the Sony HandyCam family and how these are launched over time, PALLMAR 2001 and YXKULL & PALLMAR 2002.

When the competitors were ready with a competitive product, Sony launched the next generation of HandyCams. This new generation is based on the existing modules except from a few updated modules, which have been updated with new features and technologies. These new modules are illustrated with the blocks in the second, third, fourth and fifth rows (Figure 18).

Not only does Sony compete with the competitors on new features, but they also lower the price on the old generations of HandyCams. By this approach Sony was able to compete on price and new features, i.e. low-end and high-end products. As it is illustrated in Figure 18, Sony was able to do this with five generations of the HandyCam.

How Sony contributes to this research

One of the key reasons for Sony being successful with this product family was that Sony

from the start had planned how the product family should evolve over time. Not all modules were developed from the start, but modules that were introduced to the market were prepared with:

- A plan for new features and how/where to implement
- Standardisation of interface to meet new version of modules
- Implementation of functionality in existing modules, even though these were not utilised until later when new version of modules were introduced

Planning how a product family should evolve over time with new variants is a central point for the development of the business for a given product family. Consequently, it is therefore also a central point of the definitions of architecture and standard designs. The planning aspect is a central point for applying architectures as it is fundamental if standard design is to be re-used. Nevertheless, few authors emphasise on this aspects.

7.3 Case: Philips Consumer Electronics

This research has been involved in implementation of architectures and standard designs at Bang & Olufsen. The approach at Bang & Olufsen is inspired by Philips Consumer Electronics. Several benchmarking activities have been carried out between Bang & Olufsen and Philips (meetings and method studies, PHILIPS 2000, PHILIPS 2001A, PHILIPS 2001A and PHILIPS 2001B, PHILIPS 2001C). What is presented here is only what Philips and other authors have published NIEUWLAND 1999, NIEUWLAND 2000 and SANCHEZ 2000B.

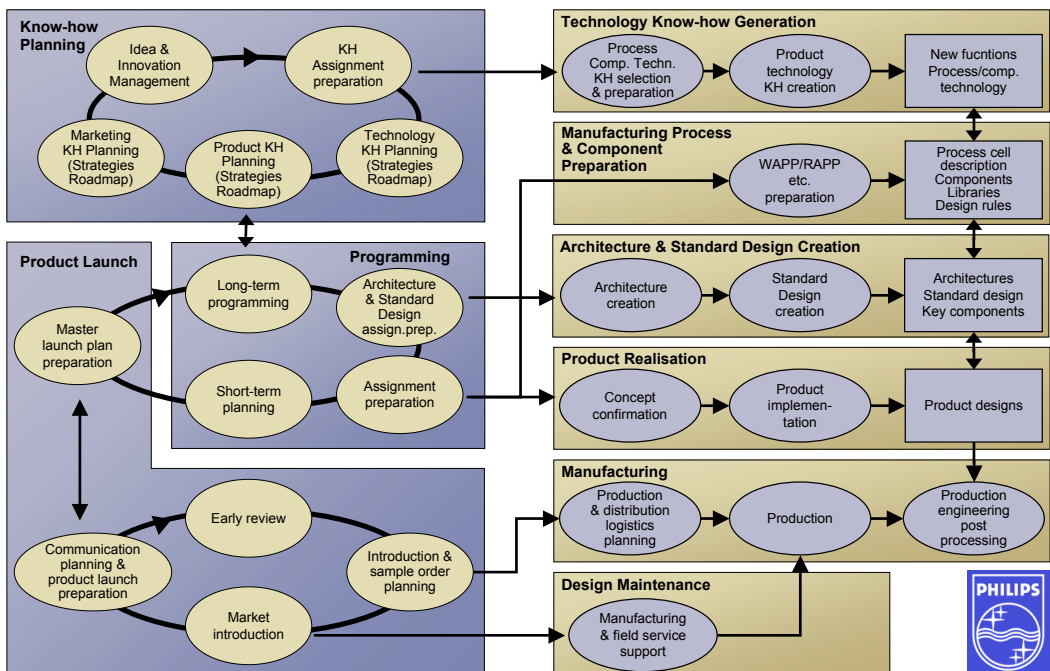


Figure 19. The Philips development model. The activities listed in the left side of the model relate to planning, whereas the activities in the right side of the model deal with development/realisation, NIEUWLAND 2000.

The development model applied by Philips is divided into two sets of activities, namely *planning* (Left side of Figure 19) and *realization* (Right side of Figure 19). The planning activities describe all activities related to the planning of products, technologies, standard designs, architectures and market introductions. The right side of the model includes all the activities related to the development of products, technologies, standard designs and reference architectures.

Philips defines “A reference architecture documents (1) the partitioning of a product family into subsystems and components (2) the interfaces in between the subsystems and with the environment and (3) the guidelines and constraints governing the design an application of the subsystems”, PHILIPS 2000.

Philips defines “A standard design is the (physical) realisation of a subsystem which complies with one or more reference architectures and is designed for re-use/multiple use”, PHILIPS 2000.

The planning activities are again divided into *Know-how planning*, *Programming and Product launch*. The Know-how planning focuses on analysing business opportunities, i.e. new product ideas, technologies, markets, etc. The results from these analyses are represented in roadmaps. It is worth noticing that so far no decisions are made on what opportunities to pursue and implement. It is a matter of mapping the opportunities. In Programming all the opportunities are evaluated and coordinated into one roadmap. Here decisions are made on what opportunities to implement and resources are allocated for implementation. The Product launch activities deal with planning, preparing and developing the market introduction.

The right side of the development model (Realization, Figure 19) is divided into Technology know-how generation, Manufacturing process & component preparation, Architecture & standard design creation, Product realization, Manufacturing and Design maintenance. *Technology know-how generation* includes traditional development and maturation of new technologies, before these technologies are implemented in products, standard designs and reference architectures. *Manufacturing process & component preparation* include development and maturation of new production technologies and preparation of new key components.

The *Architecture & standard design creation* describes the activities related to the development of the reference architectures and the standard designs. One important note here is that these reference architectures and standard designs are fully developed, tested and documented before they are offered to the product projects. The reason for this is to reduce the risk – the risk of implementing a standard design that is not ready yet. If the standard designs are not 100% ready at the point where the product project is initiated, the product will not include that standard design.

Other activities are *Product realization* and *Manufacturing*. Product realization relates to the development of the products and manufacturing relates to the development of the production system. These two sets of activities are coordinated in accordance with traditional Integrated Product Development, ANDREASEN & HEIN 1987.

Not all products are based on standard designs and platforms. Philips distinguishes between peak, optimised and standard design based products:

- *Peak products* – Products that include technology, which is still not mature enough to be included in a standard design. These products are developed independently in order to

not “damage” the standard designs and architectures.

- *Optimised products* – Price competition is very hard on some markets and in these cases products are often cost optimised independently of the standard designs and architectures.
- *Standard design based products* – Products that are based on a standard design, where one or more subsystems are re-used across product families.

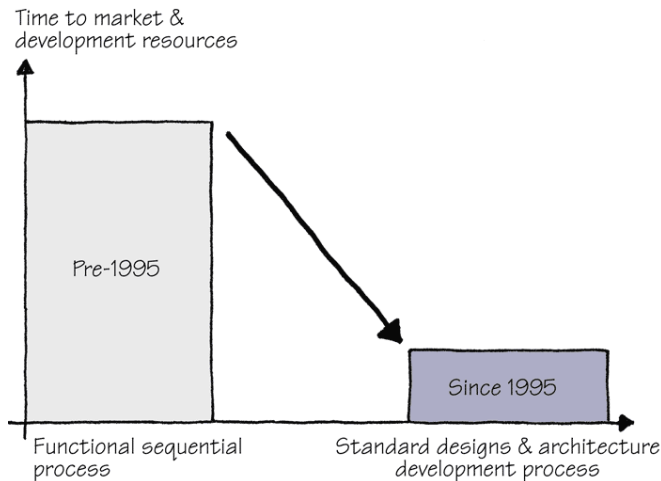


Figure 20. Time-to-market and development resources have been reduced at Philip Consumer Electronics, due to introduction of standard designs and architectures. It is claimed that Philips Consumer Electronics is four times faster in bringing new product to the market, SANCHEZ 1999b.

According to SANCHEZ 1999b Philips is four times faster in bringing new products to the market after 1995 than before 1995 (Figure 20). SANCHEZ 1999b claims that one of the main reasons for this is that Philips introduced standard designs and architectures. Philips also claims that they are more precise in hitting the time-to-market. This mainly due to how risk is handled, i.e. a standard design has to be tested before it is offered to the market. This risk issue is, however not, documented in the available literature.

How Philips Consumer Electronics contributes to this research

Philips Consumer Electronics is the company with the most extensive and well documentation platform approach that this research has come across. This appears from their extensive documentation PHILIPS 2000, PHILIPS 2001b, PHILIPS 2001a AND PHILIPS 2001c. The staff who have participated in the benchmarking activities also give an impression of a deep insight into the phenomenon of developing product families based on architectures. The key learning points from Philips are:

- *Planning vs. executing* – Much emphasis is on planning. Good and reliable plans are essential for re-use of architectures and standard designs. The planning is separated from the design activities.
- *Design split* – Philips distinguishes clearly between design preparation (development of standard designs and architectures) and execution (development of products). It is

claimed that the standard designs are fully designed and tested before they are offered to the product projects. In principle, a product project cannot be initiated based upon a standard design if the standard design is not fully tested.

- *Not all products are based on standard designs* – Distinguishing between peak, optimised and standard design based products.

The approach applied by Philips is included in this research as it has been one of the key inspirations for this research. Also Bang & Olufsen finds this approach very inspiring (“Bang & Olufsen case: From reactive to proactive re-use”, Page 132). The concepts of architecture and standard design formulated in this research reflect many of idea presented by Philips on the subject (“Towards a vocabulary for architectures”, Page 77). The approach applied by Philip not only influences the definitions, but also on the application aspects of applying architectures and standard designs. This means that aspects related to responsibility, planning and documentation are influenced by Philips.

7.4 Case: Migatronic

The following case is mainly based on FABRICIUS 1994 and interviews within the company (Migatronic). In the 90’s, Migatronic was the first company to launch portable welding machines. The portable welding machine was very well received by the customers, but unfortunately it also had some quality problems in production. It was not possible to test functionality of the whole product until all parts were assembled. Due to a complex wiring system, diagnosis of errors was difficult. In some environments dust came onto the printed circuit boards causing malfunction.

Shortly after Migatronic launched the portable welding machine, Finnish and German producers also launched portable welding machines. Migatronic studied the competitors’ products and discovered that the structure of the whole product was very different. Migatronic estimated that the production cost of the competitors’ products were 40-50% lower. It was therefore clear that Migatronic had to improve competitiveness of the portable welding machines and a cost reduction project was initiated.

As a basis for improving the welding machines relations between the product and the production were studied at four levels: corporate, family, structure and part level (Figure 21).

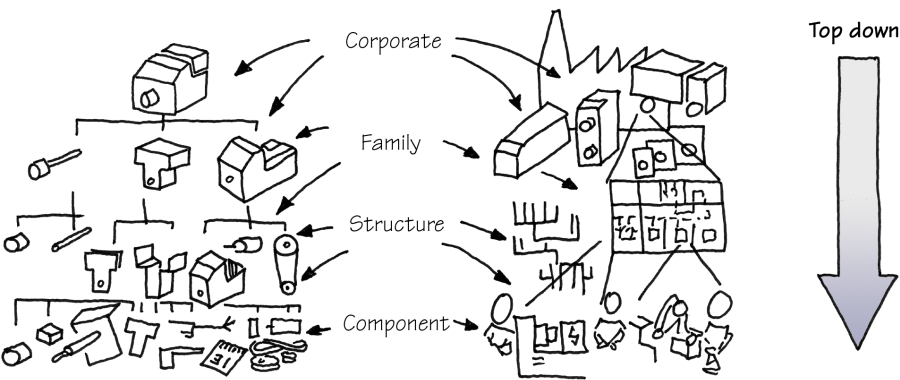


Figure 21. Types of relations between the product and the production system, OLESEN 1992.

The part level relations concern the relations between individual parts and process chains, e.g. a part is milled, surface treated and painted. Structure level relations deal with the coherence between the product structure and the layout in the production system, e.g. a stacked product structure makes it possible to choose pick & place units for assembly. Family relations are coherence between product families and their production, e.g. a certain power supply is utilised across a whole product family enabling fewer variants to be handled in assembly and increasing lot sizes. Company relations are coherence between the whole product assortment and the production system, e.g. a certain material for coolers is utilised across the whole product assortment.

The new welding machine is based on three main modules: a low voltage PCB, a high voltage PCB and an extruded aluminium section (Figure 22). Figure 23 shows the old and the new modularised welding machine.



Figure 22. The new welding machine is based on three main modules: a low voltage PCB, a high voltage PCB and an extruded aluminium section.

	Before	After
Production cost/ampere	100%	60%
Assembly time	100%	18%
Number of components	1179	520
Number of internal wires	52	0
Number of screws	119	32
Fabricated parts	102	10
Possible degree of automations	Low	High

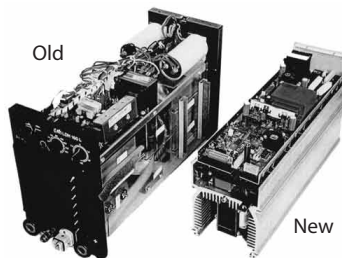


Figure 23. Left: New and old welding machine; Right: Key figures comparing the before and after situations, FABRICIUS 1994.

The main benefits obtained from the modularisation of the welding machine are shown in the table on Figure 23. In the new welding machine the amount of parts is reduced with more than 50% and assembly time is reduced with 80%. These benefits have been obtained without significant investment in production. During the design of the welding machine a central element has been systematic search for total solution alternatives on the four levels in Figure 21. This implies that both product and production are taken into consideration.

The power module of the new welding machine is also introduced in larger welding machines as illustrated in Figure 24. The number of power modules is multiplied depending on the capacity needed for the larger welding machines. The re-use of the power module enables Migatronik to run larger lot sizes in the production of the module. This scaling enables automation of the production system of the modules and hereby the cost has been lowered.

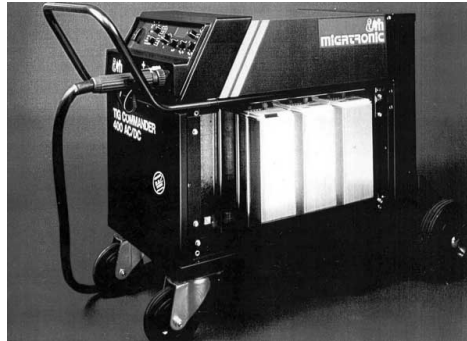
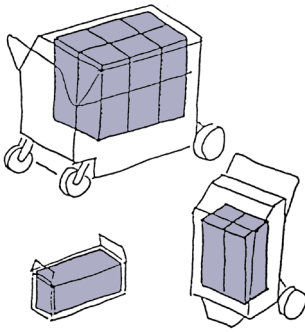


Figure 24. The power module of the new portable welding machine is used in parallel in larger welding machines, FABRICIUS 1994.

How Migatronik contributes to this research

The Migatronik case shows that modularisation and standardisation can be applied on four levels: corporate, family, structure and part level. This indicates that architecture and standard design also exist on different levels, which will be further investigated in later chapters. The power module shows how a company can benefit from re-using modules across product families. The case also shows the coherence between the development of the product concept and the production concept.

7.5 Case: Liquid analysis equipment

The next case is a company that manufactures products for measuring contents of liquids. The case is based on a one day meeting with project, engineering, production and sales managers.

One of their latest product families has been modularised, thus each parameter that the equipment can measure within a liquid is controlled by one module. Looking from a customer point of view a much more customised product can now be delivered. Each product can be configured to measure certain parameters relevant for the actual laboratory. The company has changed its sales strategy in such a way that all products are now delivered with all modules. After three months, a sales person visits the customer and they agree on how many modules that are necessary. The experience from this is that once the customer is used to being able to measure all parameters, it is difficult to live without the full functionality. As a result of this sales and profit have increased significantly.

One of the reasons that sales have increased is that customers now buy products that can measure more parameters than what they would have bought previous. Consequently, they are buying products with more functionality. Such products can be sold at a relatively higher price. Another positive side effect is that as the customers buy products that can measure more parameters, the customers also need more consumer goods such as cleaning liquids, calibration liquids, electrodes, etc. The sale of these goods has a significant impact on the business of the company.

How “liquid analysis equipment” contributes to this research

The small case shows that modularisation of product families is not just a technical issue or a way of working smarter in the R&D department. It can also be treated as a way of develop-

ing new business opportunities. In this case, the modularisation of the product family can be considered an enabler for the new sales strategy and its success.

7.6 Conclusions on state-of-the-art in industry

The above cases illustrate how architectures, standard designs, platforms and modules can be powerful tools when developing product families. VW and Philips Consumer Electronics have among others showed approaches to cost reduction and growth without increasing the R&D resources. The experiences from the Danish industry are a little more blurred. Not everyone has experienced success from developing product family based architectures, standard designs, platforms and modules. However, there is no doubt that architectures and standard designs are means to be considered when product families are developed. The benefits from these means are very promising, but the risk should also be considered.

One might argue that companies have developed product families for decades and therefore it is nothing new. That is to some extent true as history shows many examples of companies that have launched product families. However, the above cases reveal a new awareness of the potential benefits, which can be achieved by developing product families based on architectures and standard designs. This awareness leads to the new initiatives within the companies:

Management driven – Top management are aware of the business potential of architectures and standard designs. Management allocate resources and emphasises the importance of architectures and standard designs. Some of the most successful companies who apply platforms and modules have the approach as a part of their strategy, e.g. VW (PIECH 2000) and Scania (SCANIA 2001).

Standard designs vs. not standard designs – Having recognised that architectures and standard designs are beneficial, it is important to be aware that not all products should be based upon these. The way Philips distinguishes between peak, optimised and standard design based products is one way of doing so.

Holistic view – Decisions regarding the individual architectures and standard designs are not made within the projects, but are made with the entire business and product portfolio in mind. Such decisions are not left for technicians to make alone, but have to be made in coordination with management.

Performance measurement – Companies are generally very good at calculating the cost of a new product and such measurement systems tend to influence decision making. The philosophy of “you get what you measure” promotes that a measurement system for architectures and standard designs might encourage re-use. Such measurement systems should reflect re-use of parts, re-use of standard designs, re-use of production equipment, market variety, etc.

Design preparation vs. execution – Introduction of architectures and standard designs introduce new activities. Philips argues that some of these new activities should be executed outside the traditional development projects. For Philips, successful application of architectures and standard designs imply that the architectures and standard designs have to be fully developed before they are integrated into products – hence *design preparation*. This also ensures that the architectures and standard designs are developed in such a way that they are attractive for future products.

New roles and responsibilities – New activities imply new roles and responsibilities related to planning, specification, development and implementation of architectures and standard designs.

Documentation – Fundamental for re-use is that one knows what is re-used. This knowledge should be available either through personal support or documentation. Modern companies require proper documentation. This implies that architectures and standard designs should be properly documented and that the documents are maintained.

Interfaces – One of the elements of documenting architectures and standard designs are the documentation of the interfaces. The interfaces are of interest as the architectures and standard designs implement into products.

Road mapping – Application of architectures and standard designs imply a great deal of planning to align releases of architectures and standard designs with commercial releasing of products.

The above learning points have influenced this research as a mind-set for how industry works with product families.

8 State-of-the-art: Studies on research theories related to development of product families

Development of product families have gained considerable attention in industry and also the research communities are aware of the changes and challenges. The numerous publications of papers, journals and books on this subject indicate this. The objective of this chapter is to provide an overview of research contributions in this field. The chapter will not provide an exhaustive description of all theory areas utilised, but will focus on the main contributions on which this research is based.

This chapter should form a basis for the theoretical contributions within this research. The contributions should be based on existing work in this field and should clarify some of the open areas that have not been fully investigated yet. This chapter should bring answers to the following questions:

- What are the main theoretical contributions in this area?
- What are the main perception of modularisation, platform and architecture?
- What are the aspects of modularisation, platform and architecture that have not been clarified yet?

This chapter is structured by treating each of the main research contributions one by one, - describing the point of views on developing product families. Each contribution is concluded by stating what key lessons are to be learned. The chapter is ended by a conclusion on the state-of-the-art in theories related to development of product families.

8.1 Product architecture

ULRICH 1995 was one of the first persons to study the phenomenon of *product architecture* in the field of engineering design research. The phenomenon is later detailed in ULRICH & EPPINGER 2004 and by other authors. ULRICH 1995 argues that the architecture of a product is the

scheme by which the function of the product is allocated to physical components. “I define product architecture more precisely as: (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specifications of the interfaces among interacting physical components” ULRICH 1995.

The *functional elements* relate the functional structures as they are known from PAHL & BEITZ 1996 and HUBKA 1973. Figure 25 includes such functional structure. The *mapping* of functions to physical components corresponds to the coherence between the functional organ and part domains as they are described in the Theory of domains (Page 31). The third element of the concept of product architecture is the *interfaces* among interacting physical components.

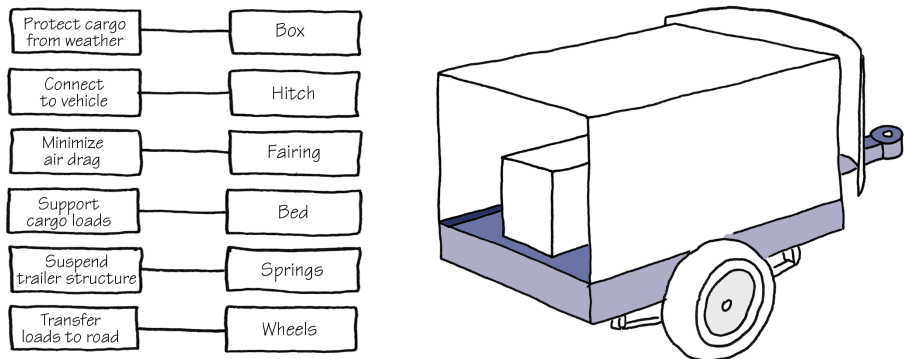


Figure 25. An example of the product architecture for a trailer. The left column of blocks represents the function structure of the trailer. The right column of blocks represents the part structure of the trailer, ULRICH 1995.

How “Product architecture” contributes to this research

The definition of product architecture by ULRICH 1995 is constituted by known elements, i.e. functional structures, mapping between functions and parts and interfaces. The primary contribution is the identification of the phenomenon of product architecture and the description of the phenomenon by known elements. Finally, ULRICH 1995 points out the importance of understanding how a product architecture can be utilised to manipulate a company’s product assortment and the related business.

The concept for product architecture, which is proposed here, seems to be widely accepted in the academia. The concept is also the starting point for this research. However, one of the goals for this research is to enhance the knowledge of phenomena architectures and standard designs. Chapter “Towards a vocabulary for architectures” (Page 77) will do so by studying the variety that can be described and managed by an architecture.

8.2 Strategic modularisation by using product, process and knowledge architectures

One of the authors to recognise that architectures can be a strategic tool for managing product families is SANCHEZ 1999B, SANCHEZ 1999A AND SANCHEZ & COLLINS 2001.

SANCHEZ 1999B distinguishes between product and process architectures. The concept of product architecture is in line with ULRICH 1995’s perception of product architecture (“Prod-

uct architecture”, Page 54). A process architecture relates to “...*decomposition of functionalities of a process into specific functions and functional activities. The full specification of the process activity interfaces – i.e. the inputs and outputs of each activity – that define how various process activities interact in the process as a system*”, SANCHEZ 1999B. SANCHEZ 2000A adds a third kind of architecture – the knowledge architecture. This kind of architecture is defined as a “*knowledge structure composed of loosely coupled knowledge domains*”.

SANCHEZ 1999B recognises the importance of alignment of the product and process architectures (Figure 26). It is when these two types of architectures are aligned and interacting as intended that the benefit of the architectures can be harvested. A good product architecture is worthless if it is not supported by a good process architecture.

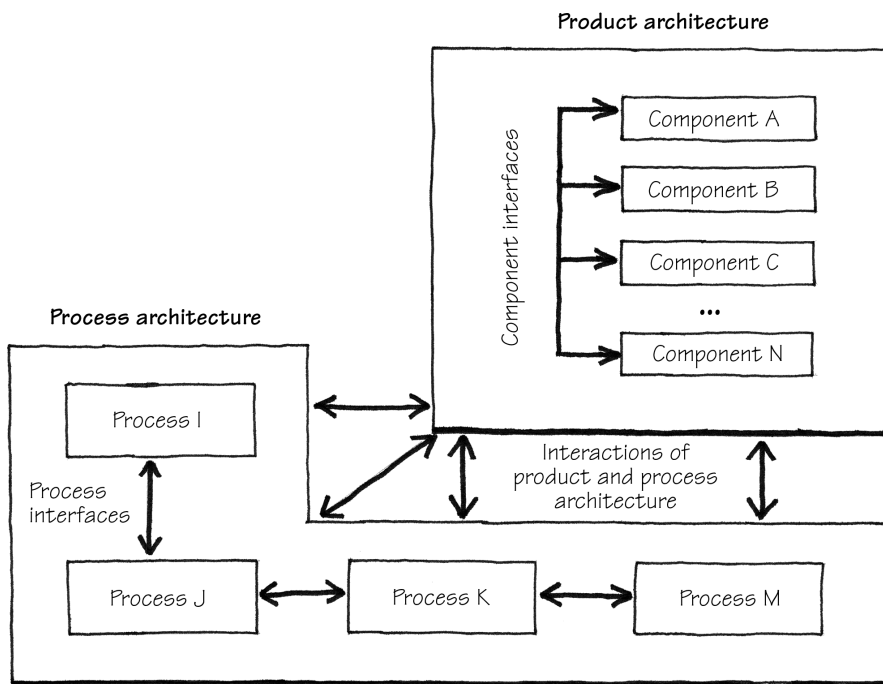


Figure 26. Interactions of product and process architectures, SANCHEZ 1999B.

How “Strategic modularisation by using product, process and knowledge architectures” contributes to this research

A key contribution from the work of SANCHEZ 1999B is the recognition of process and knowledge architectures and the importance of aligning the different types of architectures. A product architecture in itself is identical to a product structure, according to the Theory of domains (Page 31), Multiple structures (Page 33) and Genetic Design Model System (Page 34). It is when the product architecture is combined with a process and knowledge architecture that the phenomenon of an architecture makes sense.

SANCHEZ 1999B, SANCHEZ 1999A AND SANCHEZ & COLLINS 2001 also bring the architecture phenomenon from being a technical aspect to being a strategic tool for managing product families.

8.3 The power tower

Successful application of architectures, standard designs, platforms and modules often implies strategic and management attentions. One of the key contributors to this field is MEYER & LEHNERD 1997. MEYER & LEHNERD 1997 propose the so-called "Power tower" that describes the application of platforms in the market places and some of the strategic options available (Figure 27).

The power tower consists of three elements: common building blocks, product platforms and market applications. The *common building blocks* are the assets that a company builds its business upon, i.e. customer insights, product technologies, manufacturing technologies and organisational capabilities. The *product platform* is defined as: "A product platform is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced" MEYER & LEHNERD 1997. *Market applications* relate to segmentation of the market and application of platforms on the market. In the power tower the market is segmented according to user groups and product price and/or performance characteristics. Together the common building blocks, the product platform and market applications illustrate how platforms should meet with the market segments.

MEYER & LEHNERD 1997 propose four strategic approaches for introduction of platforms in the market place. Figure 28 illustrates these approaches by mapping them into the market application view that is known from Figure 27.

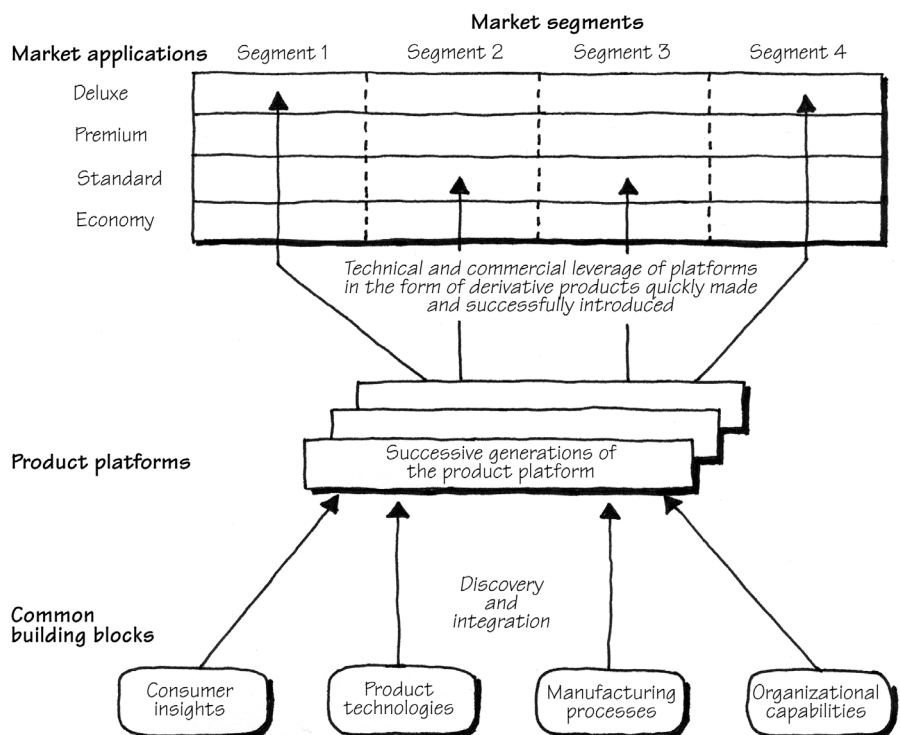


Figure 27. The power tower for platforms. The power tower is constituted by common building blocks. These form the basis for the platforms. The platforms then have to be assigned certain market applications, MEYER & LEHNERD 1997.

Niche specific platforms with little sharing of subsystems and manufacturing processes – One platform strategy is to make dedicated platforms for each individual market niche (Figure 28, top left). The result is a myriad of platforms with little sharing of subsystems and manufacturing processes.

Vertical scaling of key platform subsystems – Vertical scaling implies a strategy where the company seeks to address a range of price/performance tiers within a market segment with a common product platform (Figure 28, top right). Two variants of this strategy exist, where the initial platform is either scaled up or down to another tier of price-performance.

Horizontal leverage of key platform subsystems and manufacturing processes – A platform strategy is to have a platform that is leveraged from one market niche to the next within a given tier of price-performance (Figure 28, bottom left).

The beachhead strategy – The fourth strategy combines horizontal leverage with upward vertical scaling. This strategy is called *beachhead strategy* (Figure 28, bottom right). This strategy takes its starting point in a market segment with low cost/performance. Hereafter the platform is scaled to other segments and price/performance markets.

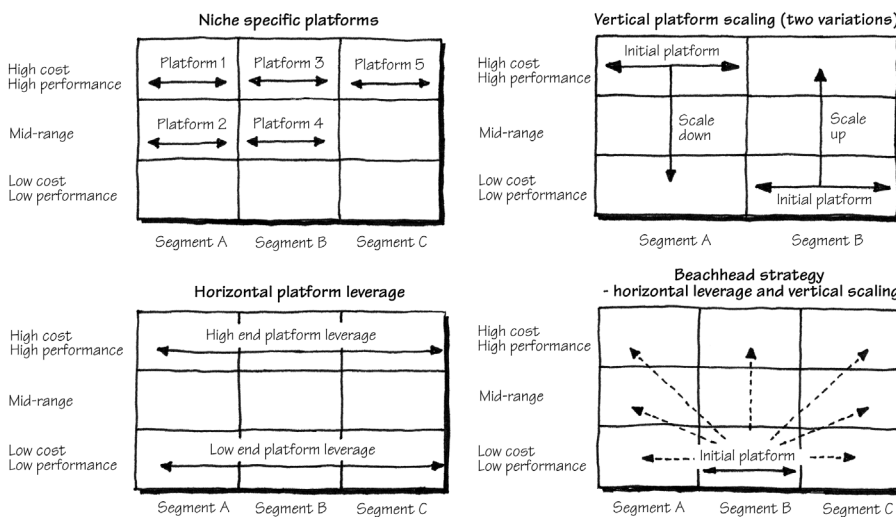


Figure 28. Four platform strategies that map platforms to market segments, MEYER & LEHNERD 1997.

How “The power tower” contributes to this research

Engineers tend to treat modularisation and platform development as a technical discipline. The “power tower” proposed by MEYER & LEHNERD 1997 shows how platforms can be applied as a strategic tool for addressing several market and cost/price segments. MEYER & LEHNERD 1997 illustrate four different platform strategies. Each platform strategy has its advantages and disadvantages. Selection of a platform strategy might therefore be crucial for a given company.

8.4 Factors influencing a platform strategy

The previous “power tower” illustrates different types of platform strategies. A research group at the Norwegian University of Science and Technology (NTNU) has studied what

factors that influence platform strategies. This group defines a platform as “a collection of core assets that are reused to achieve a competitive advantage” KRISTJANSSON ET AL. 2004. In this context assets are components, processes, knowledge, people and relationships among people. This definition is derived from literature by finding the lowest common denominator of a series of definitions.

KRISTJANSSON & HILDRE 2004 defines a platform strategy as: “A platform strategy is the overall elaborate action plan a company has to managing its platforms”. A platform strategy should elaborate and systemically plan action to manage a group of platforms, both individually, as well as group-wise.

KRISTJANSSON & HILDRE 2004 argue that the competitive advantage strategy of the company, the industrial situation, the market situation and the internal core competencies of a company have to be studied and understood in order to propose a platform strategy. Table 3 lists factors that a company has to consider as a platform strategy is formulated.

Areas	Factors	Suggestions regarding the platform strategy
Core competencies	Identifying present core competency platforms	Core competencies must be used; the competencies of a company should be platformed.
Industry situation	Threat of new entrants	A company should strive to use platforms in a way that increases barriers to entry.
	Bargaining power of suppliers	Suppliers should not have too much bargaining power in reference to platforms.
	Bargaining power of buyers	Bargaining power affects the decision of what to include in a platform. If bargaining power is high, platform threshold and performance and focus on excitement add-ons to differentiate.
	Threat of substitute products or services	Substitutes are bought either due to cost or differentiation. Platform to minimise threat.
	Rivalry among existing firms	If rivalry is high, platform the commodity part.
	Clock speed / innovation pace	Platform low paced assets. Platform mid- and high paced depending on volume and volatility.
	Proprietary vs. open source	Open source SW platforms might be useful where the need to establish a standard is large.
	Maturity level	Usually a high maturity level indicates a focus on cost rather than innovation and technology. Platform commodity and differentiate
	Disruptive technologies	If threat of disruptive technologies is high, the platform should not contain the as-is technology.
Market situation	Kano's model of customer satisfaction	Depending on volatility, platform threshold and possibly performance.
	High- or low involvement products	Buyers find high involvement products risky. Platforms in high involvement products should decrease the feeling of risk.
	Volatility	High volatility indicates a need for flexibility. Platform accordingly.
Competitive strategy	Differentiation	Platform threshold assets.
	Cost leadership	Platform threshold and performance assets.
	Focus	Knowledge platform of importance.
	Market plan	Does the company have products in different price segments, industry segments or family segments. Do not platform differentiating assets.

Table 3. KRISTJANSSON & HILDRE 2004 provide a summarisation of factors that a platform strategy must consider.

How “Factors influencing a platform strategy” contributes to this research

The research from the research group at the NTNU contributes to this research by pointing out the importance of platform strategies. They argue that different platform strategies are appropriate for different types of businesses. They have identified different factors that might influence a platform strategy. These factors show the multifaceted task of identification of a platform strategy.

8.5 Functional structures as a basis for modularisation

One of the spokesmen for “functional structures”, which also form basis for product architecture as described previous is Kevin Otto and his research group. His group uses the functional structures as a basis for identification of modules that can be re-used across different product families.

According to ZAMIROWSKI & OTTO 1999 and SUDJIANTO & OTTO 2001 the function structures explicitly relate the functions through flows. A function structure connects sub functions with flows of energy, material and information. Figure 29 illustrates an example of a functional structure that forms a basis for modularisation to support multiple brand platforms. Each block in Figure 29 represents a function. The blocks that are not shaded, are the common functions used in all product families.

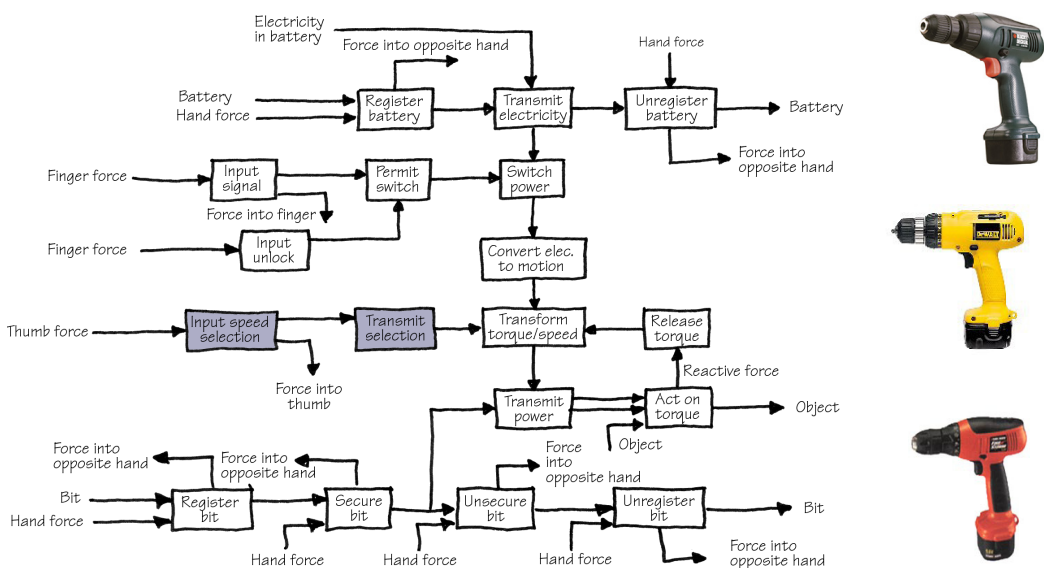


Figure 29. Example of a functional structure as a basis for modularisation of multi brands/products. The structure represents 5 product brands/products: Black & Decker, Firestorm, Quantum, DeWalt and VersaPak, SUDJIANTO & OTTO 2001.

How “Functional structures as a basis for modularisation” contribute to this research

A functional structure seems to be fundamental for defining platforms, standard designs and architectures. Many authors who work with platforms and architectures refer to such structures. SUDJIANTO & OTTO 2001 propose a concept for modelling functional structures.

They also illustrate how these structures can be applied for modelling product families as a basis for modularisation of multiple brand platforms.

The functional structure is in this research used as a basis for investigating the phenomena of architectures and standard designs (Towards a vocabulary for architectures, Page 77). Also, the modelling formalism proposed in the above is further developed for modelling architectures and standard designs for product families ("Tool: Generic organ diagram", Page 100).

8.6 Design structure matrix

One of the approaches that is widely accepted in the academia for decomposing a product into standard designs, modules or platforms, is the "Design structure matrix". Particularly the American research communities practise this approach, e.g. www.dsmweb.org. The type of design structure matrixes that are related to this research are the so-called "component-based".

The objective of a design structure matrix is to encapsulate subsystems or components into modules/chunks. This is done by studying the interfaces and interactions among the subsystems/components and hereby proposing a module structure with limited interactions among the modules/chunks, BALDWIN & CLARK 2000.

Before clustering

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Radiator	A	X														
Engine fan	B	X	B													
Heater core	C			C												X
Heater hoses	D			D												
Condenser	E	X			E	X		X								
Compressor	F				X	F		X	X							
Evaporator case	G						G									X
Evaporator core	H				X	X		H	X							X
Accumulator	I					X		X	I							
Refrigeration controls	J									J						
Air controls	K										K					
Sensors	L											L				
Command distribution	M												M			
Actuators	N													N		
Blower controls	O														O	X
Blower motor	P			X			X	X							X	P

After clustering

	D	J	K	I	M	N	A	B	E	F	I	H	C	P	O	G
Radiator	D															
Engine fan	J		J													
Heater core	K			K												
Heater hoses	L				L											
Condenser	M					M										
Compressor	N						N									
Evaporator case	A							A	X							
Evaporator core	B							X	B	X						
Accumulator	E							X	E		X					
Refrigeration controls	F							X	F	X	X					
Air controls	I							X	I	X						
Sensors	H							X	X	X	H			X		
Command distribution	C												C	X		
Actuators	P												X	X	P	X
Blower controls	O													X	O	
Blower motor	G													X		G

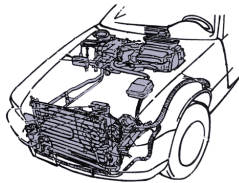


Figure 30. The example of a design structure matrix for the climate control system of an automobile. The top matrix shows a matrix in which no clustering has been applied, whereas the bottom matrix shows the result of a clustering, PIMMLER & EPPINGER 1994.

In a design structure matrix the subsystems are listed as a row and a column (Figure 30). Their labels and order are the same. An “X” in the matrix indicates an interaction among two subsystems. PIMMLER & EPPINGER 1994 define four classes of interactions:

- *Spatial* – A spatial-type interaction identifies needs for adjacency or orientation between two elements.
- *Energy* – An energy-type interaction identifies needs for energy transfer between two elements.
- *Information* – An information-type interaction identifies needs for information or signal exchange between two elements.
- *Material* – A material-type interaction identifies needs for materials exchange between two elements.

Figure 30 illustrates an example of a design structure matrix for the climate control system of an automobile. By using algorithms it is possible to encapsulate components into modules or chunks that are closely related to each other from an interaction point of view (e.g. STEWARD, V 1981). This process is referred to as “clustering”. In other words, clusters absorb most, if not all, of the interactions (i.e. “X”) internally and the interactions or links between separate clusters is eliminated or at least minimised.

Figure 30 includes two design structure matrixes for the climate control system of an automobile. The top matrix is the original. The bottom matrix reflects the result from clustering. The blue areas in the matrix indicate potential modules/standard designs.

How the “Design structure matrix” contributes to this research

The basic idea of the design structure matrix is to study the interfaces and interactions among the components/subsystem and based upon this to propose a module structure with a “simple” structure. Like previous authors, the spokesmen for the design structure matrix take their starting point in a structure similar to the previously defined architectures.

The structure proposed from application of a design structure matrix has focus on interfaces and interactions. However, other authors argue that a module structure might be reasoned in other aspects than interfaces/interactions, e.g. ERIXON 1998. Such reason can be ability to source sub suppliers for development of modules. The types of reason are investigated further in section “Module drivers” (Page 64).

Many companies experience the challenges of a growing product assortment and one of the reasons for introducing modularisation, platforms, standard designs or architectures is to ease the handling of variety. However, the design structure matrix does not propose how to handle variety.

In order to be able to draw out a design structure matrix one must have deep insight into the product which is to be developed. One must know nearly all components, subsystems, interfaces and interactions. Otherwise, it will be impossible to fill in the matrix in a proper way. This implies that the matrix is best applicable for re-design of existing products, whereas radical new product concepts are more difficult to model in a design structure matrix.

The design structure matrix in itself will not be applied in this research. But the mindset related to understanding the importance of interfaces and interactions among components,

subsystems, modules and standard designs is one of the corner stones for the contributions of this research.

8.7 Design for variety

F.J. Erens takes up the topic of designing product families in his thesis “The Synthesis of Variety”, ERENS 1996. ERENS 1996 argues that a domain-oriented approach for modular design is needed. This implies that one should understand the relations between the functional, the technological (i.e. organ structure) and the physical structures of the product family. This viewpoint is identical to the Domain theory approach (Page 31).

ERENS 1996 proposes ways to formally define and document modular products. As a product family can be defined in three domains: the functional domain, the technology domain and the physical domain, each domain has one product model and a number of representations.

According to ERENS 1996, a product architecture is essential to separate the stable and variable parts of the design. The stable aspects create a framework within which a variety of products can be developed. The standardisation of interfaces in one domain improves the possibility to combine components in such a way that a large variety in that domain is created. The architecture of a product family is decoupled from the architectures of its components. The variety of these components has no consequences for external interface of these components, which reduces design complexity.

How “Design for variety” contributes to this research

Taking into consideration that ERENS 1996 completed this thesis early in the history of modularisation, these conclusions are very thorough. One of the key learning points from ERENS 1996 is that three domains are needed for describing product families. ERENS 1996 applied the functional domain, a technological domain and a physical domain for product families (Figure 31). This viewpoint is identical to the Domain theory approach (Page 31).

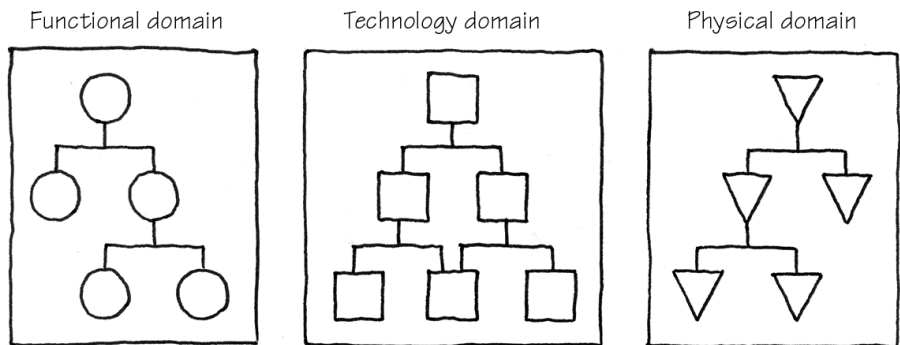


Figure 31. A product family can be defined in three domains: the functional, technology and physical domains. Each domain has one product model and a number of representation, ERENS 1996.

8.8 Baukasten system

Every day engineers re-use subsystems regardless of these re-used subsystems are denoted modules, platforms, standard designs or architectures. Elder literature in the field of engi-

neering design also treats this phenomenon. During the Bauhaus era (1919 to 1933) the German architect Walter Gropius, was one of the first who combined the idea of standardisation with functional thinking and industrial production in building construction, DROSTE 1990. These building blocks were denoted Baukasten. In practise these Baukasten were functional units, e.g. kitchen, living room, sleeping room, etc.

BOROWSKI 1961 develops the concepts of Baukasten further:

- *“A building set [Baukasten] is a collection of well-known, different elements from which different things can be put together.”* BOROWSKI 1961, translated from German by MILLER 2001.
- *“The building set system [Baukasten System] is a structuring principle, which, based on a combinatorial plan [Bauprogramm] or a specimen plan [Baumusterplan], specify the composition of a limited or unlimited number of things within a certain application area from a number of standardised building blocks.”* BOROWSKI 1961, translated from German by MILLER 2001.

Borowski's focus was mainly mechanical systems, i.e. machine elements as dominant for that period before the emergence of microprocessors. The Baukasten are mainly seen as physical entities with simple geometric interfaces.

How the “Baukasten system” contributes to this research

MILLER 2001 concludes in his studies of Borowski's work: *“Borowski touches the following issues in relation to building set systems: (1) building blocks as design units in addition to the plain parts, (2) combinations of variants from a stockpile of building blocks, (3) uniform industrial design appearance, (4) possibility of up-grade and adaptation, (5) tolerances of interfaces to ensure compatibility, (6) different consumption of building blocks, (7) intertwinement of different building set systems.”*

One of the major changes in the field of engineering design since Borowski did his work, is the degree of variety that companies have to handle. The variety is among other things caused by the degree of customisation that today's customers ask for.

8.9 Module drivers

One of the contributions on modularisation, which has showed a wide acceptance in the academia and industry, is produced by ERIXON 1998. One of Erixon's primary theoretical contributions is the formulation of a set of “module drivers”. These drivers expressed various reasons for modularisation. The list below includes the module drivers (ERIXON 1998 and ERICSSON & ERIXON 1999):

Carry over – They are reasons that a technical solution should be a separate module since the solution can be carried over to future generations of the product.

Technology evolution – Technical solutions that go through a technology evolution during the product's life cycle should be separated into a module. This might enable update of the module without updating the entire product.

Planned product changes – There are reasons that a technical solution should be a separate module because it is the carrier of properties that will be changed according to a decided development plan. These changes are developed in-house or by sub suppliers.

Technical specification – Technical solutions that are often influenced by variations in technical specification (different: function, size, torque, etc.) can with advantage be separated into a module.

Style – Some parts of the product might be strongly influenced by fashion or trends. It can be beneficial to isolate these parts into a module in order to differentiate the appearance of the products.

Common unit – Parts that are identical in all products are candidates for “common unit” modules. A common unit is used across several products.

Process and/or organisation re-use – Parts of a product that require the same production processes can be clustered into a module. Such clustering might improve the efficiency of the production.

Separate testing – The possibility of separate testing of each module before assembly might improve quality. This is mainly due to the reduction of feedback times.

Supplier offers black box – Sub suppliers might be suitable for development and manufacturing of modules. This implies that the vendor takes the manufacturing, development and quality responsibility.

Service and maintenance – Parts exposed to service and maintenance may be clustered together to form service modules.

Upgrading – Designing modules that allow upgrading of the product, offer customers the possibility of changing the product in the future.

Recycle – There are reasons that this technical solution should be a separate module because of recycle issues, e.g. to isolate highly polluting material.

How “Module drivers” contribute to this research

ERIXON 1998 focuses in his work on identification of modules and the effects that modularisation can provide. The module drivers contribute with a differentiated perception of what a module is and why a technical solution should be a module. ERIXON 1998 differentiates by stating that modularisation is not just about encapsulation of parts and standardisation of interfaces. The module drivers show that the reasons for introducing modules are not only found in the technical domain, but are also reasoned in the life phase systems, e.g. the ability to upgrade the product after purchase of the product.

One of the limitations of the work from ERIXON 1998 and his group is the ability to deal with and describe variety. Their approach is to encapsulate the variety in few modules and make these modules interchangeable. However, variety in product families often show a complex pattern, where variety is distributed in several parts, subsystems or modules.

ERIXON 1998 applies the module drivers as a basis for identification of modules by means of the MFD procedure (Modular Functional Deployment). The MFD procedure is described in the following.

8.10 Modular function deployment

Modular function deployment (MFD) is a structured approach for modularisation of products. This approach is based on the work of ERIXON 1998 and module drivers (Page 64).

The MFD approach consists of five tools that are linked together (Figure 32). The objective of MFD is to identify the modules of a given product. The starting point is the identification of customer requirements. These are represented in a QFD-matrix, where they are linked to the properties of the product. The second step is to identify the functions and corresponding technical solutions. In the third step the technical solutions are analysed regarding their reasons for being modules. A central part of this evaluation is the application of the module drivers (Page 64). The outcome of the third step is module candidates. In the fourth step the modules are analysed according to interfaces, lead times, cost, etc. In the final step specifications are made for each module.

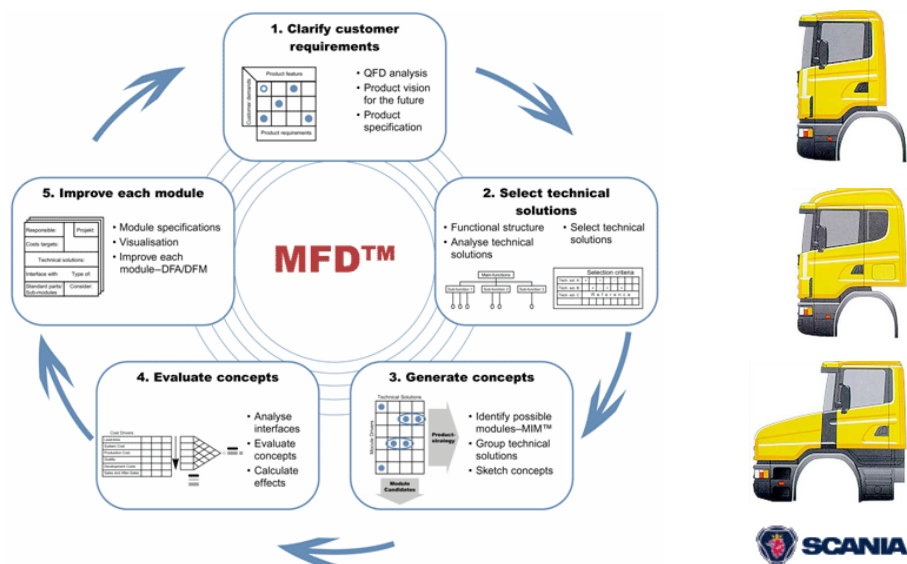


Figure 32. Left figure: Five step procedure for identification of modules.

Right figures: The procedure has been applied for Scania truck cabs. ERICSSON & ERIXON 1999.

How “Modular function deployment” contributes to this research

MFD is a coherent approach for identification of modules that has its starting point in customer requirements and the module drivers. In this way the MFD approach touches some of the central parts of the identification of modules.

The MFD approach is a little weak in the aspects of identification and design of variety. The variety issue is mainly considered as a matter of what modules that should include variety. Smart solutions for variety are often related to smart handling of variety in life phase systems, i.e. production, sales, etc. Such considerations are not treated directly by the MFD approach.

It seems that the MFD approach is applicable for identification of modules for products that are rather mature and where the technical solutions are well known. One could argue that the MFD approach supports “re-clustering” of well known technical solution based on module drivers and interfaces. The MFD approach does not in itself encourage for radical new product concepts with new technologies.

8.11 Aligning modularisation and the configuration processes

One of the research groups, who have studied the topic of product families from a configuration and modularisation point of view, is the Laboratory of Product Design and Development at the Institute of Production Engineering, Tampere University of Technology, Finland.

Configuration refers to the definition of a product instance that is being derived from a pre-defined set of building blocks (parts or modules) by relating them with pre-defined methods, PULKKINEN ET AL. 2004. Configuration is applied as means for managing product variety within sales, projecting, ordering and engineering processes.

PULKKINEN 2000 argues that product families are rarely configurable. This means that the product families often are complex and it is difficult to describe how components and modules can be combined into commercial products. PULKKINEN 2000 suggests modularisation of the product family as a means for simplifying the implementation of a configuration system. Proper modularisation or re-structuring of the product family can lead to simpler and more easily maintained configuration systems.

In a study done by the research group, 10 companies have been studied to learn from the companies' experiences from the applications of modularisation and configuration, PULKKINEN ET AL. 2003. It is stated that:

- *Mass customisation and one-of-a-kind companies* – One group of the companies starts from businesses that offer products that are customised and projected to meet the customers' needs. Their goal is to improve productivity as they tailor the products to meet the customers' needs. This is achieved by decomposing the product into modules. The modules can be tailored and combined in different ways. The combination and tailoring of modules is controlled by configuration knowledge, which is often acquired into a configuration system. Some of the companies have applied an approach called partial configuration, where a section of the product instance is engineered instead of pure configuration.
- *Mass production companies* – The second group of companies produces products based on serial and batch production principles. Their goal is to improve customer satisfaction and reduce work in progress. In these companies the modules are standardised subsystems that are produced on larger batch series. Re-using such modules implies re-use of their properties, e.g. quality.

The studied companies have different experiences from application of modularisation and configuration, PULKKINEN ET AL. 2003. Some of the companies have applied the approaches with success, whereas others have failed. The companies with success are characterised by a clear and stable business environment as well as success in product structuring and configuration process, which include successful changes of the business processes. The companies that fail find the changing of the business processes difficult, because they have underestimated the complexity of the business processes and the importance of changing the processes to benefit from the restructuring of the product.

How “Aligning modularisation and the configuration processes” contributes to this research

The research from the research group at Tampere University of Technology contributes to

this research by pointing out the importance of managing variety within product families. Their approach towards management of variety within product families is the application of configuration systems. It is argued that re-structuring of the product family (e.g. modularisation) is often necessary in order to implement a configuration system.

It is also pointed out that successful re-structuring of product families and implementation of configurations systems often demand re-design of the business processes in order to benefit from the re-structuring of the product family and the configuration system.

8.12 Modular engineering

MILLER 2001 uses the term *modular engineering* for a design approach aiming to create a match between modular architectures of artefact, activity and design models/knowledge to gain synergy effects from modularisation. An architecture is according to MILLER 2001 different from a structure. Structure is a generic term that relates to elements and their relations in systems. An architecture is the scheme by which a system is consciously divided into subsystems including specifications on interfaces. It is the result of a deliberate design process aiming to utilise commonalities among a range of deliverables, ANDREASEN 1998.

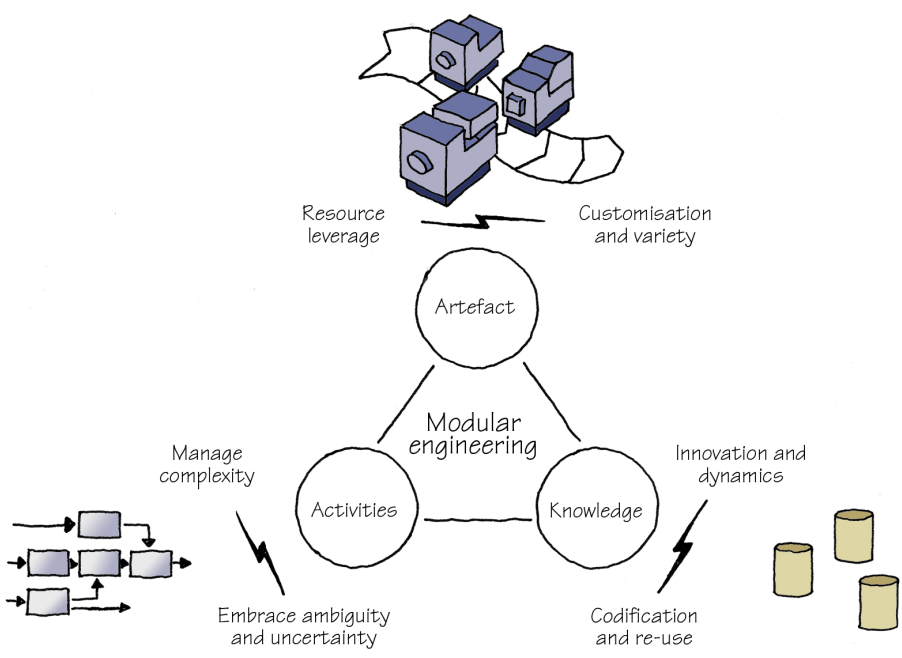


Figure 33. Modular engineering implies modular architectures of artefacts as well as activities and knowledge, MILLER 2001.

MILLER 2001 distinguishes between artefact, activity and knowledge architectures (Figure 33). An artefact architecture is what other authors denote as product architecture. An activity architecture relates to decomposition of activities into sub-activities and tasks, including specifications on expected deliverables and interfaces to other activities. The activity architecture is similar to the way SANCHEZ 1999B distinguishes between product and process architectures. A knowledge architecture is the scheme by which knowledge of a company, as residing in the heads of employees and written down in documents, is divided into

knowledge domains. This approach is similar to SANCHEZ 2000A.

How “Modular engineering” contributes to this research

A central part of modular engineering as it is proposed by MILLER 2001 is the coherent architectures, i.e. artefact, activity and knowledge architectures. This approach is in many ways similar to the definitions of SANCHEZ 1999B and SANCHEZ 2000A. However, MILLER 2001 shows how this approach can be applied for modularisation of production systems.

8.13 Conclusions on state-of-the-art in research

This chapter provided an overview of some of the key contributions related to research within the field of developing product families. Within the scope of this chapter, the following conclusions can be presented:

Functional decomposition – There seems to be agreement among the authors that the architectures are essential for developing product families. This applies for single products, product families, modularised products and platform based products. Normally, an architecture has its starting point in a functional decomposition of the product or product family. This implies that the product is decomposed into functions and/or subsystems. Based upon this decomposition the architecture is defined.

Domains – Even though the general perception is that an architecture is primarily described by means of functions, there are other authors who points out other domains for defining architecture. ERENS 1996 argues that a domain-oriented approach for modular design is needed. This implies that one should understand the relations between the functional, the technological (i.e. organ structure) and the physical structures of the product family. SANCHEZ 1999B and SANCHEZ 2000A distinguish between product, process and knowledge architectures. SANCHEZ 1999B and MILLER 2001 also point out the importance of alignment of the product, process and knowledge architectures.

Interfaces – As the architecture is defined, the interfaces within the architecture are defined. It is the general perception that these interfaces are important for the success of the architecture. This implies that these interfaces should be managed and sometimes even standardised.

Strategic – Several authors point out that application of architectures, standard designs, modules and platforms for product families can be of strategic importance for a company's business. This implies that defining the architecture is not just a technical discipline related to development of product families. It might as well be a task related to development of a company's business. The decomposition of a product into an architecture can therefore be reasoned in all functional areas within the company (i.e. R&D, purchase, etc.) as well as life phase systems (i.e. production, test, sales, service, etc.)

The theoretical contributions presented in the present chapter are used in the following chapters to understand and define the phenomena of architecture, standard design and platform.

9 Conclusions on state-of-the-art in developing product families

In Part 2 a number of contributions on development of product families have been presented. The contributions represent state-of-the-art studies from industry (Page 43) and research theories (Page 54). Table 4 includes a classification of these contributions based on the “Framework for investigating the phenomenon of developing product families” (Page 42).

The left column of Table 4 lists the elements of the framework, as previously described (Page 42). Along the top row of Table 4, the different contributions on the topic are listed. An “X” in the table indicates what area of the framework a given contribution focuses on.

Having reviewed exiting literature on the phenomenon of developing product families, it is clear that many authors have contributed to understanding the phenomena. The literature study also shows that the authors have different viewpoints and focus on this topic. Even though many have contributed to this research area, it is also clear that there is room for further contribution. Some of the areas that should be further investigated are:

- *Elements of an architecture* – The general understanding of product architecture suggests that a product architecture is composed by functions, subsystems and/or interfaces. However, such definitions are very much similar to a definition of a structure. A product architecture is a structure, but it is also meaningful structuring. This implies that the architecture is created to obtain an effect, e.g. enable re-use of standard designs, ease service, etc. There is a need for further investigation of the elements of a product architecture, i.e. what are the elements of a product architecture?
- *Variety* – One of the challenges for companies who work with product families, is the handling of variety. Platforms, standard designs and architectures can be seen as means for dealing with variety in a smart manner. However, the existing definitions of architecture tell little about how to represent variety with a product architecture. There is a need for further investigation of how to represent variety within a product architecture.
- *Modelling of architecture* – The modelling approaches for product architectures found in the literature take their starting point in block diagrams and matrixes (e.g. Design structure matrix). More detailed and formal representations of architectures would be beneficial.
- *Modelling of variety* – As little literature deals with handling variety within architecture, only few modelling approaches exist. There is a need for detailed and formal representations of variety. Not just from an architecture point of view, but in general.

Part 3 goes into details with defining concepts of architecture and standard design.

Contributors															
	Case: VW, Page 46	Case: Sony HandyCam, Page 48	Case: Philips Consumer Electronics, Page 50	Case: Migatron, Page 53	Case: Liquid analysis equipment, Page 55	Product architecture, Page 58	Strategic modularisation by using product, process and knowledge architectures, Page 59	The power tower, Page 60	Factors influencing a platform strategy, Page 63	Functional structures as a basis for modularisation, Page 64	Design structure matrix, Page 65	Design for variety, Page 67	Baukasten system, Page 68	Module drivers, Page 69	Modular function deployment, Page 70
Main viewpoints															
Objects of manipulation															
Product family	X	X	X	X	X		X	X	X	X		X	X		X
Single product				X		X				X	X		X	X	X
Service system							X								
Activity and process							X								X
Research phenomena															
Platform	X		X					X	X						
Architecture		X	X			X				X		X			X
Module		X	X	X	X						X		X	X	X
Effects to be harvested															
Reduction of cost	X			X				X	X				X	X	X
Increase of quality	X			X									X	X	
Reduction of time-to-market	X	X	X		X			X	X					X	X
Quicker response to market changes	X	X	X		X			X						X	X
High degree of variety	X	X	X		X			X					X	X	X
Impact areas															
Engineering	X	X	X			X		X	X	X	X	X		X	X
Maintenance				X										X	X
Purchase	X							X						X	X
Logistic	X													X	X
Production	X			X				X	X					X	X
Sales		X			X				X					X	X
Service				X	X									X	X
After sales					X									X	X
Organisational levels															
Strategic level	X	X	X				X	X	X						
Tactical level	X	X	X											X	
Operational level			X	X		X				X	X	X	X		X
Design phases															
Planning of architecture		X	X				X	X	X						
Specification of architecture		X	X			X				X				X	X
Development of architecture			X			X				X	X		X		X
Documentation of architecture			X								X	X			
Implementation of architecture in product project			X												
Underlying technical disciplines															
Mechanical	X			X		X			X		X	X		X	X
Electrical	X			X		X					X	X		X	X
Software											X	X			
Mechatronic		X	X					X	X	X	X	X		X	X
Types of business															
Mass production		X	X	X		X		X	X	X	X	X		X	X
Mass customisation	X							X	X			X	X	X	X
One-of-a-kind													X	X	X

Table 4. Classification of main focuses in technical literature on development of product families.

Part 3

Contribution to a theory of architectures for product families

Part 3 contributes to a theory of architectures for product families. The contribution distinguishes between architectures, platforms, modules, design units and standard designs. Part 3 includes definitions and descriptions of the concepts.

Exploration of literature on the phenomenon of developing product families reveals that the concepts of architecture, standard design, platform and module are central to understand. The study in Part 2 shows that many authors emphasise the importance of applying these concepts. But few authors investigate the nature of architecture based on the artefact theories, e.g. Theory of technical systems and Theory of Domains. Part 3 investigates the phenomenon further. To do so, the concepts of architectures, platforms, modules, design units and standard designs are used.

Part 3 brings answers to the following questions:

- What are the concepts needed for defining architecture?
- How do we define these concepts?

In this research two hypotheses are formulated for product families based on architectures (Page 21). These hypotheses focus on defining the concepts of architecture and standard designs. Part 3 will explore these hypotheses.

Structure of Part 3 – The starting point of Part 3 is the formulation of a vocabulary for architectures. The vocabulary focuses on describing the structure of architectures. The vocabulary is constituted by the terms architecture, platform, design unit and standard designs. These terms are treated from product, product family and product assortment points of view. Part 3 concludes by highlighting the contributions of this part and how it meets with the hypotheses.

10 Framing the concepts of architecture and standard design

In this research two hypotheses are formulated for product families based on architectures (hypotheses no. 1 and 2). The objective of Part 3 is to verify the hypotheses for product families based on architectures. A part of this verification is to formulate a vocabulary for architectures and standard designs. This particular chapter frames aspects needed for formulating a vocabulary. It starts by re-capturing the hypotheses. These are explored further to set a frame for the vocabulary for architectures.

10.1 Framing hypothesis no. 1 - Architecture

The first hypothesis aims at understanding the concept of architecture. The second hypothesis aims at understanding the elements of an architecture, i.e. standard designs. The hypothesis on architecture is repeated below (see also Page 21).

Hypothesis no. 1 – Architecture

It is possible to identify a model that is able to describe and document the building principle for individual products within a product family. This model, which is named “architecture” consists of the following elements: design units, standard designs, interfaces and application characteristics. Designing within such an architecture enables re-use of building principles and standard designs.

This hypothesis states that re-use of design entities (i.e. standard designs) is enabled by means of an architecture. The architecture describes the building principle by which the standard designs can be re-used within a product family. The hypothesis states that an architecture consists of design units, interfaces and application characteristics (Figure 1).

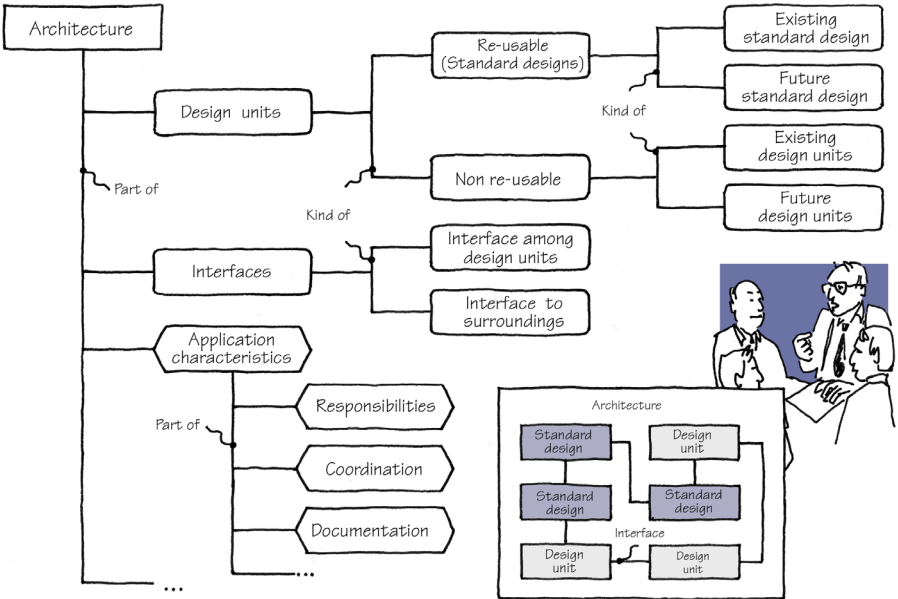


Figure 34. Entity-relationship model on defining architecture. Primary elements of an architecture are design units, standard designs, interfaces and application elements.

The entity-relationship model in Figure 34 illustrates some of the aspects that are relevant when defining a vocabulary for product families based on architectures. These aspects are:

- *Design units to re-use vs. design units not to re-use* – The hypotheses claims that among other things an architecture is defined by design units. These design units are subsystems of a product or product family. These subsystems are denoted *design units*. Design units are design entities: organs, parts, assemblies, modules, standard designs, etc. The design unit serves the purpose of encapsulating a part of a design into manageable units. Not everything within a product family should be re-used from one product family to another. However, the architecture of the product family should be able to deal with design units that are re-used as well as those that are not re-used. Design units that are re-used are denoted *standard designs*.
- *Existing vs. future design units* – As a product family is designed focus is often on the design units (assemblies, modules, standard designs, etc.) that are under development, i.e. existing solutions. Whereas, design units that are to be developed in the future (i.e. future design units) have low priority. However, successful development of product families often require that design units are re-used from one product generation to another and new features are added to the product family over time. To enable this, existing design units might need extra interfaces and functionalities, which will only be utilised in the future. A vocabulary for product families based on architectures should enable distinction between existing and future design units. Such distinction should exist for design units as well as standard designs.
- *Interfaces among design units* – All components and all design units have interfaces (individual interfaces), but product families have a new class of interfaces, i.e. generic interfaces. The generic interfaces are those that enable design units to work together and these have to be stable over generations in order to enable re-use across product families and generations of product families. The interfaces should be a part of the definition of an architecture.
- *Interfaces to surroundings* – Besides interfaces among design units and standard designs, an architecture includes another type of interfaces. These interfaces are those connecting the design units and the standard designs with the surroundings, e.g. input/output signals, power, external network, etc. An architecture should include these interfaces as these can have impact on the architecture. An example could be the interfaces to a television. Interfaces such as those known from the computer industry (e.g. LAN, USB, FireWire/1394, etc.) have significant impact of the functionality that should be supplied by the television architecture.
- *Application of architectures* – Architectures do not arise by themselves. Architectures are a product of a conscious development of product families and the desire to re-use subsystems across several products. Successful application of architecture means that someone in the R&D department is responsible for the development, implementation and maintenance. In other words, someone should have the responsibility for the architecture.
- *Coordination with other initiatives* – As architectures are developed, these should be developed in agreement with other initiatives within the company. An architecture should be aligned with technologies applied in the product portfolio, features offered to the market and existing/future standard designs.

- *Documentation of architecture* – Decisions regarding architectures need to be documented in order to be available for the other members of the organisation who carry out the development, implementation and maintenance of the architectures or standard designs.

10.2 Framing hypothesis no. 2 – Standard design

The second hypothesis of this research focuses on the element of the architecture, which is re-used, i.e. standard design. The standard design is an essential element of an architecture. The second hypothesis deals with understanding what a standard design is. The hypothesis on standard design is repeated below (see also Page 22).

Hypothesis no. 2 – Standard design

It is possible to describe re-usable solutions by means of three classes of characteristics - structural, functional and application characteristics. The re-usable solutions are denoted "standard designs". These three classes are necessary and sufficient for enabling re-use.

Previous introduction of the concept of a standard design states that a standard design is an encapsulation of organs and parts into an entity that can be re-used in several products (Page 22). A standard design is described by its *elements*, *functional properties* and the *application characteristics* of standard design (Figure 35).

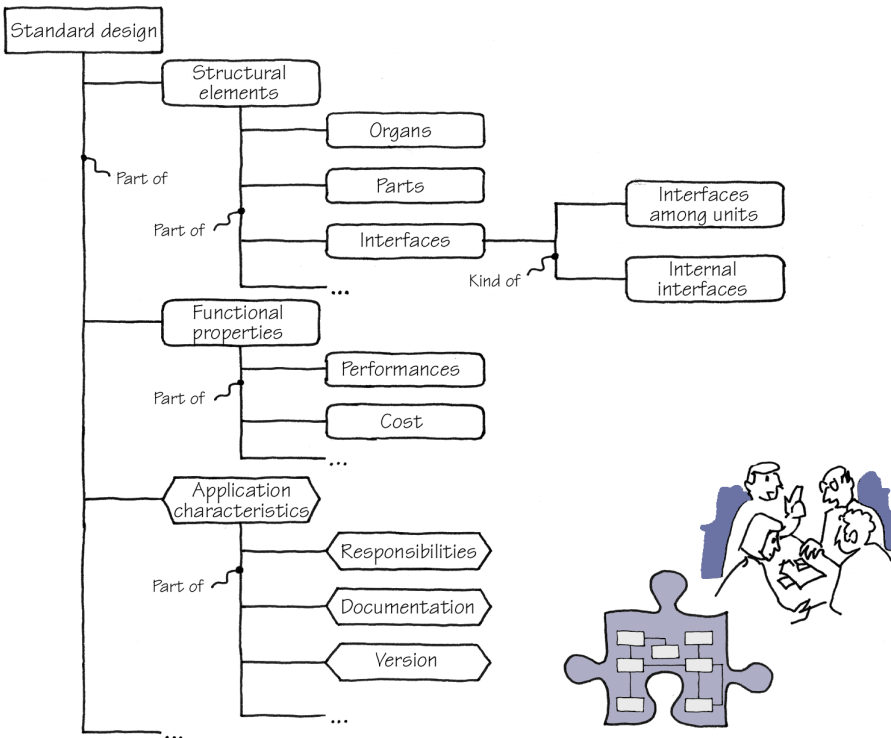


Figure 35. Entity-relationship model for standard designs. Primary elements are structural elements, functional properties and application characteristics.

The hypothesis on architecture states that an architecture among other things consists of design units. It is also argued that some of the design units are re-used and these are denoted *standard designs*. Finally, the hypothesis on architecture states that the design units and the standard designs can either be present or introduced later on. The hypothesis on standard design and Figure 35 claim that a standard design can be described by structural elements, functional properties and application characteristics:

- *Structural elements* – A design unit is an encapsulation of design entities and has elements. It is likely that organs and parts, which are formulated by the Theory of domains, are the structural elements of a design unit. This implies that a design unit is constituted by organs and parts.
- *Internal interfaces* – Standard designs could be considered “black boxes”. However, to fully understand an architecture and understand how a standard design functions, it can at times be necessary to model the internal parts of the standard designs, i.e. parts and organs. These parts and organs are connected by means of interfaces. Such interfaces should be a part of the definition of a standard design.
- *Interfaces among units* – The interfaces “out of” the standard design are of importance in order to communicate and function with other standard designs or design units. Consequently, these interfaces should be a part of the definition of a standard design.
- *Functional properties* – The behaviour of the standard design is relevant as it becomes a part of the behaviour of the final product. Standard designs should therefore be described by means of functional properties. Such properties are related to the performance, e.g. temperature, cost, etc.
- *Application of a standard design* – Application aspects that are applicable for architectures are also relevant for standard designs. This implies that issues such as responsibility, coordination and documentation are also relevant for standard designs.

The section “State-of-the-art: Studies on research theories” (Page 54) and the section “State-of-the-art: Studies on development of product families in industry” (Page 42) reveal that other authors have described many of the above issues. However, none of the authors treat all the aspects or name them. Also, the authors have different theoretical bases, which they use as they define the phenomena. The following includes a contribution to a vocabulary for developing product families based on architectures. The vocabulary strives to include the above aspects and to relate them to the Theory of technical systems (Page 30) and the Theory of domains (Page 31).

The vocabulary to be formulated in the following is constituted by design unit, standard design, module, architecture, assortment architecture, family architecture, product architecture, platform, assortment platform, family platform, product platform, architecture alignment and platform alignment.

11 Towards a vocabulary for architectures

This chapter strives to contribute with a vocabulary for product families based on architectures. Hereafter, the vocabulary is formulated including the concepts of architectures, platforms, modules, design units and standard designs.

11.1 Design unit, standard design and module

From literature it is learned that an architecture is constituted by functions (e.g. ULRICH 1995), chunks (e.g. ULRICH & EPPINGER 2004), modules (e.g. ERICSSON & ERIXON 1999) or standard designs (e.g. PHILIPS 2000). According to the Theory of domains, such an object is called a *design unit*, MORTENSEN & ANDREASEN 1996. In the following there is distinguished between three classes of design units, i.e. design unit, standard design and module (Figure 36).

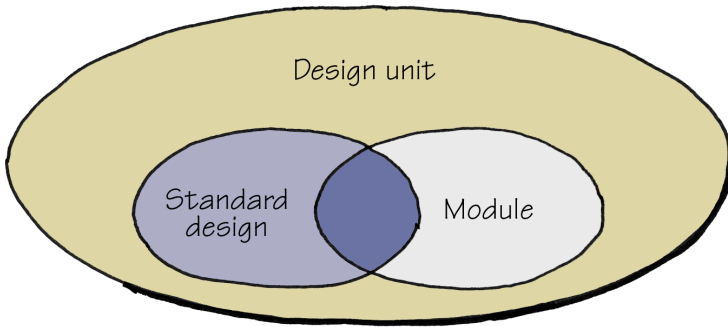


Figure 36. A design unit is a super class for a standard design and modules.

Design unit

According to MORTENSEN & ANDREASEN 1996 a design unit is a function, organ, part or an encapsulation of a group of these. The design unit serves the purpose of encapsulating a part of the design into manageable units for the purpose of designing and modelling. In the case of working with product families, the purpose of encapsulating parts of a product, is to enable re-use of these parts and to enable modelling of these units.

MORTENSEN & ANDREASEN 1996 postulate that synthesis of a product consists of creating design units. The sum of design units constitutes the product (Figure 37).

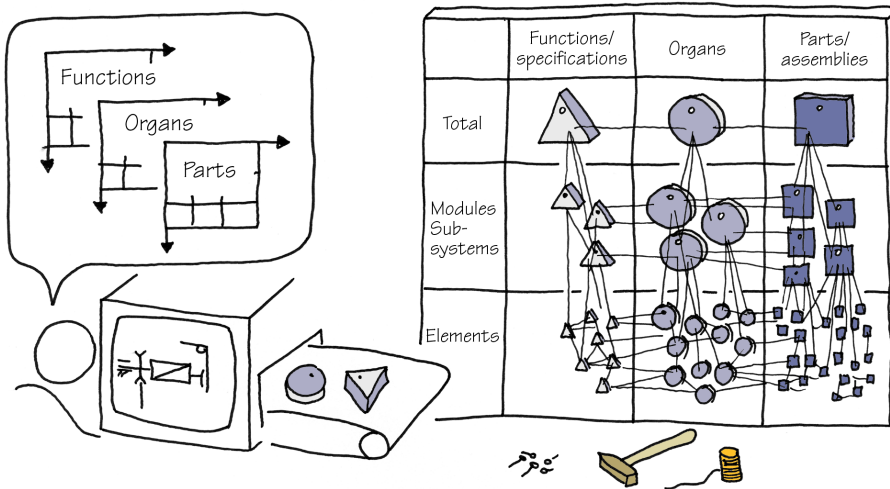


Figure 37. A scenario for designing with design units: The designer creates design units, utilising the concepts of the Domain theory MORTENSEN & ANDREASEN 1996.

A design unit that is a function is determined by identification of a subject, which creates the effect affecting an object. A design unit thus has effect relations to other design units perceived as objects. A design unit that is an organ is determined by identification of an internal organ.

The design unit phenomenon is recursive, which means that a design unit can consist of other design units. The encapsulation of a design unit depends on the designer's viewpoint.

An example of a design unit for television products at Bang & Olufsen could be an inferred receiver. An inferred receiver is used for receiving a control signal from a remote control and pre-processing the signal for the television.

Definition of a design unit

A design unit is a function, organ, part or an encapsulation of a group of these. The design units together constitute a product, MORTENSEN & ANDREASEN 1996.

Standard design

The term standard design is inspired by the Philips Consumer Electronics term for a module that is re-used, NIEUWLAND 1999. A standard design is a design unit that complies with one or more product families that will be developed over time. To be more precise, a standard design has to comply with what later on is called "assortment architecture" (Page 83) and/or "family architecture" (Page 84). Standard designs are about re-using over time, i.e. re-use of physical designs or design principles. A standard design is an encapsulation of software, electronics and/or mechanics to a self-contained functional unit.

Examples of standard designs in the audio industry are DVD-drive, hard drive, power supply, FM-tuner, etc. However, such design units are not considered standard designs, unless they comply with the following three rules:

- *Decision of re-use* – A design unit is not a standard design until it has been decided that it will be used in more than one product. This is normally prescribed by what we later will introduce as the assortment architecture (Page 83) and/or family architecture (Page 84).
- *Documentation* – A standard design has to be documented in such a way that it is possible to implement the standard design for newcomers. This implies that interfaces and design rules for implementing of the standard design have to be documented. An example of such documentation guidelines for standard designs is described in "The first standard designs at Bang & Olufsen" (Page 144).
- *Responsibility* – The standard design organisation (i.e. standard design manager) has the ownership of the standard design. The standard design manager guides the implementation, design changes of the standard design, etc.

All products in the audio industry have a power supply, but that does not make the power supply a standard design. Neither, if two products use the same power supply. The power supply has to comply with the above rules.

Definition of a standard design

A standard design is a design unit that complies with one or more product families that will be developed over time. Furthermore, the standard design has to comply with the rules: decision of re-use, documentation and responsibility.

Abstract standard designs

A central point regarding standard designs is that they are flexible and re-used on different levels. Ideally, standard designs should be re-used 100% from one product to another product. However, there are cases where the standard design has to be modified in order to fit to the product, e.g. due to physical constraints caused by the industrial design. Such modification can be a small (e.g. change of a tolerance) or large (e.g. changes in the PCB layout). This implies that a standard design does not necessarily have to be re-used 100%.

The phenomenon of having abstract design units is described by ANDREASEN 1980 as illustrated in Figure 38. This model has originally been used for describing how a design unit is synthesised in each domain (i.e. functions, organs and parts) by making the design unit more concrete and more detailed. Each domain has the dimensions abstract/concrete and un-detailed/detailed. When a design is made more concrete, more attributes are determined, such as dimensions, materials, etc. When a design is made more detailed, more elements are determined. This model also explains that even though a standard design is not re-used physically, the concept of the standard design can still be re-used more or less concrete/detailed.

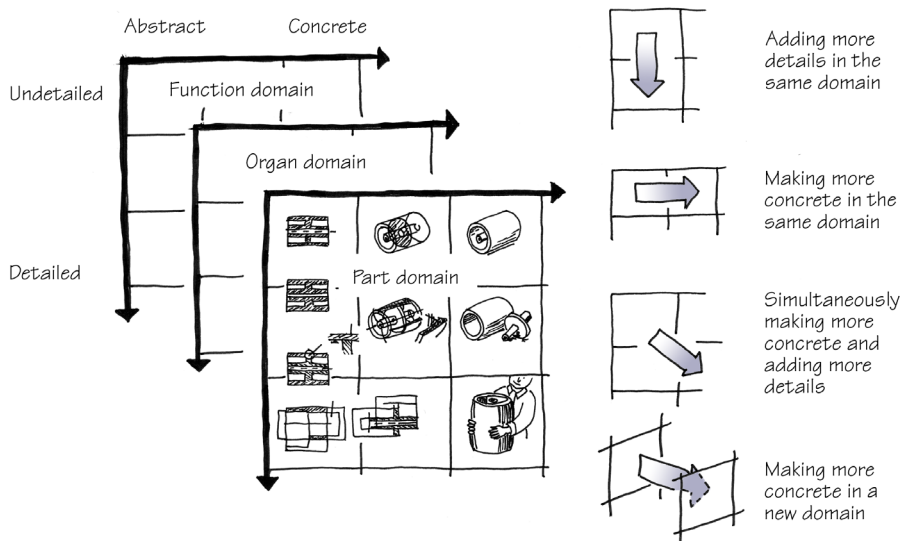


Figure 38. The Theory of domains (ANDREASEN 1980) contains a notion of sequence in the process of designing a product, where each domain is characterised by its abstraction and complexity, after BUUR 1990 and OLESEN 1992.

At Bang & Olufsen the metaphor “showcase” (In Danish “vitrineskab”) is used as a metaphor for illustrating that standard designs can be re-used on different levels (Figure 39). The showcase illustrates that the standard designs are “on the shelf solutions”. Each standard design has one showcase. The same standard design can be found on different shelves in

the same showcase. The shelves symbolise the different levels. The bottom shelf symbolizes a standard design that can be re-used 100% and the top shelf symbolizes the lowest degree of re-use, where the design principle is re-used (e.g. function diagram). Several attempts have been made to define the different levels of re-use, but no satisfactory definition has been made, yet. However, the showcase has proven to be a meaningful metaphor for discussing the application of standard designs within a company.

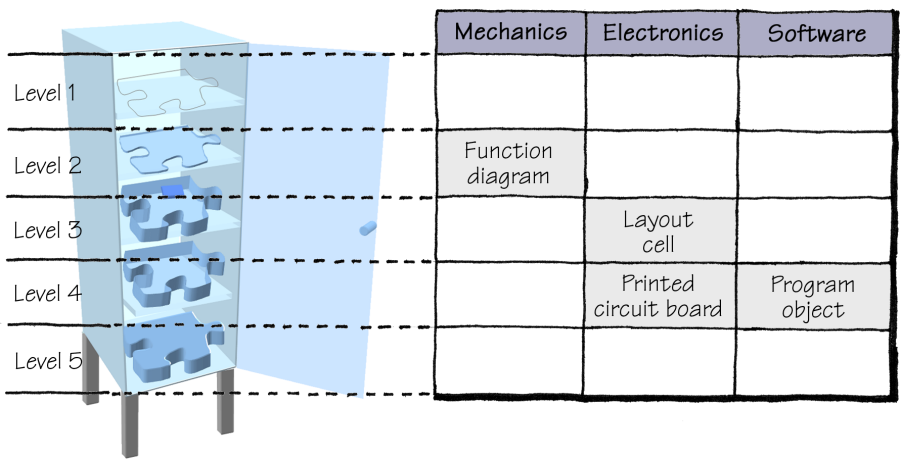


Figure 39. Showcase for “on the shelf standard designs”. A showcase is applied at Bang & Olufsen for communication of how standard designs can be re-used more or less concrete/detailed.

Module

This research applies the term “module” as it is used by ERICSSON & ERIXON 1999. They state that a module is an encapsulation of one or more design units into a physical entity. Furthermore, a module has to comply with one or more module drivers, ERICSSON & ERIXON 1999 (Page 64). In other words, a module is an encapsulation that is reasoned in order to achieve an effect. An example of a module that is created to achieve an effect is a printer cartridge for inkjet printers. The cartridge is designed in such a way that it can be changed when it is empty. Hereby, the customer can change the cartridge when needed and the company can have a profitable business by selling the cartridges.

Definition of a module
A module is one or more design units that are encapsulated into a module and that comply with the module drivers.

This implies that a standard design can be a module, but is not necessarily so, if it does not comply with the module drivers.

11.2 Architecture

The architecture describes how a product or several product families are partitioned into standard designs and design units and how functionality is allocated to the different standard designs and design units. The architecture describes the building principle of a product or several product families. This implies that the architecture describes how standard de-

signs and design units can be combined into specific products.

Like the standard designs, an architecture is constituted by software, electronics and/or mechanics. An architecture is often illustrated by means of a high level block diagram including all standard designs and their interfaces (Figure 40).

The scope of an architecture is wider than just the standard designs. It also includes functionalities that are not re-used, but are only implemented once, i.e. design units. Even though these design units should not be re-used, it is important to include them in the architecture, because other standard designs will have to interface with these design units. Developing standard designs that are not prepared for the design units might imply that the standard design is not re-usable for products with these design units.

Examples of such functionalities (design units) that are not developed as standard designs, but still included in the architectures at Bang & Olufsen, are the first hard drives for audio recording. Bang & Olufsen has already these hard drives in portfolio and many future products will include hard drives. Despite this, the hard drives have not been developed as standard designs. This is mainly because the technology is not mature enough for Bang & Olufsen and because Bang & Olufsen has not clearly defined how hard drives should support the product strategy in the long run, i.e. what functionality does the customer need and what industrial standard should be implemented. Developing hard drive solutions as standard designs would be too risky and too resource consuming at the moment.

Other examples from Bang & Olufsen are mechanics that moves e.g. movable antennas, DVD-loaders, turning tables for TV, etc. These are not developed as standard designs, because they vary from product to product due to the industrial design. However, the architectures and the standard designs are prepared for these design units by means of standardised interfaces and control systems. Otherwise, it would never be possible to re-use any of the standard designs.

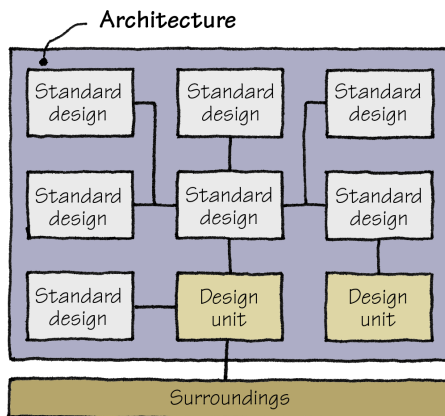


Figure 40. Symbolic representation an architecture. An architecture consists of design units, standard designs, their interfaces and interfaces to the surroundings.

Note that a product or product family does not by default have an architecture. An architecture only exists if the product or product family includes standard designs that comply with the previous definitions of standard designs (Page 79).

Also, the architecture describes the interfaces among the standard designs, design units and the surroundings, e.g. external network. The surroundings are not a part of the architecture, but the interfaces are. The reason is that many products, in one way or another, have to interact or communicate with the surroundings. Consequently, the interfaces to the surroundings are of importance since they can influence on the functionality of a product.

The symbolic representation of an architecture in Figure 40 shows an architecture that includes standard designs, design units and their interfaces. Figure 40 also reveals that interfaces to the surroundings are a part of the definition of an architecture.

According to FABRICIUS 1994, Design for Manufacture is relevant on four different levels within a company, i.e. corporate, family, structure and component levels (Figure 21). The corporate level describes the interaction between the product and other types of company products. Family level describes the relationship between the different variants in the same product family. Structural level describes the relationship between the different subsystems/components. Finally, the component level describes the design/specification of each individual component.

The top three levels are also applicable for architecture and platforms. This means that architectures and platforms exist on these three levels. In the following, the levels are labelled *assortment*, *family* and *product* levels. Consequently, the following will distinguish between assortment, family and product architectures. Architecture is the general term for assortment, family and product architectures.

Definition of an architecture

An architecture is a structural description of a product assortment, a product family or a product. The architecture is constituted by standard designs and/or design units. The architecture includes interfaces among units and interfaces with the surroundings.

Assortment architecture

An assortment architecture is a class of architectures that covers a product assortment. The symbolic representation of an assortment architecture in Figure 41 is similar to general architecture shown in Figure 40. This implies that it includes standard designs, design units and interfaces among the units and interfaces with the surroundings. The diagram in Figure 41 differentiates from Figure 40 in the way it includes standard designs and design units that have not been developed yet. The *future* standard designs and *future* design units are marked with dotted lines.

Depending on the type of industry the assortment architecture should look 3 to 5 years ahead. This implies that the assortment architecture should include new coming products, features, technologies and standard designs. Consequently, one of the key disciplines is to cultivate road mapping. In some industries new assortment architectures will be developed with a certain interval. In other industries it is not an option to develop new assortment architectures. For these companies the assortment architectures have to be continuously updated and renewed in order to be up-to-date at all times. For these companies an inadequate assortment architecture can be disastrous for the business.

In the R&D department for television products at Bang & Olufsen it is the general opinion that they will never have the resources to develop a brand-new assortment architecture for the television portfolio. However, it should be no surprise to anyone that the future

television will be digital. The only way to achieve this will be to gradually let the analogue assortment architecture evolve to a digital assortment architecture and hereby gradually introduce the digital television. The challenge is to do this without introducing extra costs and quality problems and to ensure that the timing is correct for the market and the technologies.

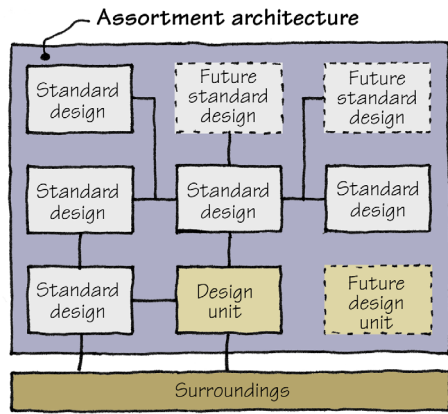


Figure 41. Symbolic representation of an assortment architecture. The assortment architecture differs from the symbolic architecture representation (Figure 40) by also including future standard designs and future design units.

Definition of an assortment architecture

An assortment architecture is an architecture that covers a product assortment. An assortment architecture is constituted by existing standard designs, existing design units, future standard designs and future design units. The architecture includes interfaces among the units and interfaces with the surroundings.

Family architecture

A family architecture is an architecture that covers a product family, whereas an assortment architecture covers several product families, i.e. an assortment.

The symbolic representation of a family architecture in Figure 42 is based on the assortment architecture illustrated in Figure 41. Other family architectures could be derived from the same assortment architecture.

Definition of a family architecture

A family architecture is a class of architectures that covers a product family. A family architecture is constituted by existing standard designs, existing design units, future standard designs and future design units. The architecture includes interfaces among the units and interfaces with the surroundings.

Product architecture

A product architecture is an instance of a family architecture. Meaning that every individual product has a product architecture. In principle a product architecture is only valid for one specific product.

The symbolic representation of a product architecture in Figure 43 is based on the family architecture illustrated in Figure 42. Other product architectures could be derived from the same family architecture.

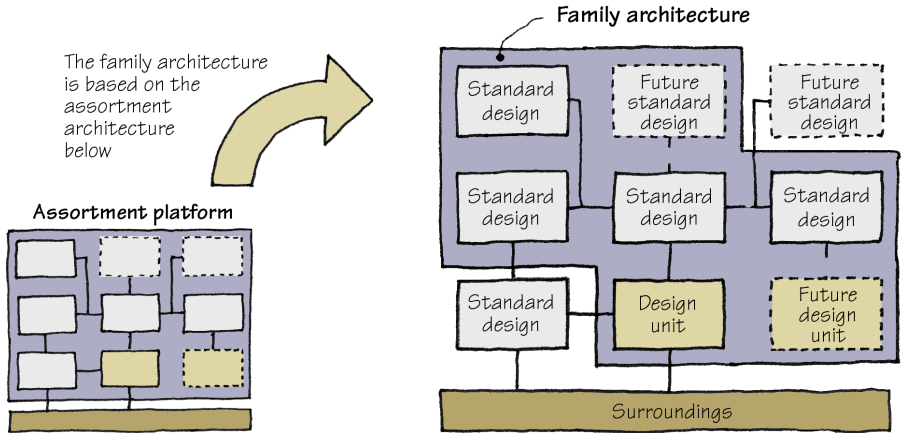


Figure 42. Symbolic representation of a family architecture that is based on the assortment architecture illustrated in Figure 41.

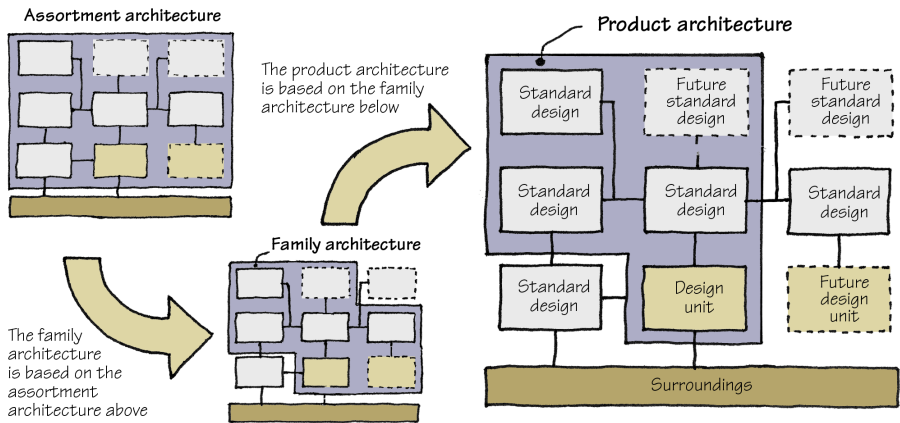


Figure 43. Symbolic representation of a product architecture that is based on the family architecture illustrated in Figure 42.

Definition of a product architecture

A product architecture is a class of architectures that covers one individual product. A product architecture is constituted by existing standard designs, existing design units, future standard designs and future design units. The architecture includes interfaces among the units and interfaces with the surroundings.

11.3 Platform

A platform is a physical instance of a part of an architecture that only includes standard designs that exist. A platform describes how the existing product assortment, product family

or product is derived from an architecture. Whereas an architecture “looks into the future”, the platform only describes the products and standard designs that have been implemented so far. One could say that a platform is the physical realisation of standard designs and an architecture that can be identified in the production and service systems.

Definition of a platform

A platform is a structural description of a product assortment, product family or a product. A platform is an instance of an architecture that only includes existing standard designs and their interfaces, i.e. interfaces among the standard design, interfaces among standard designs and design unit and/or interfaces among standard designs and the surroundings.

Consequently, a platform is constituted by standard designs and interfaces, i.e. interfaces among the standard design, interfaces among standard designs and design unit and interfaces among standard designs and the surroundings. It is noticed that design units, future design units and future standard designs are not part of a platform. Consequently, a platform also differs from an architecture by not including design units, future design units and future standard designs.

Assortment platform

An assortment platform follows the general definition of a platform. However, an assortment platform is the subset of an assortment architecture that is used across several product families.

The symbolic representation of an assortment platform Figure 44 is based on the assortment architecture illustrated in Figure 41.

Notice in Figure 44 that none of the future standard designs, which are marked with dashed lines, are included in the platform. The reason is that a platform only includes existing standard designs, whereas the architecture also includes future standard designs and design units.

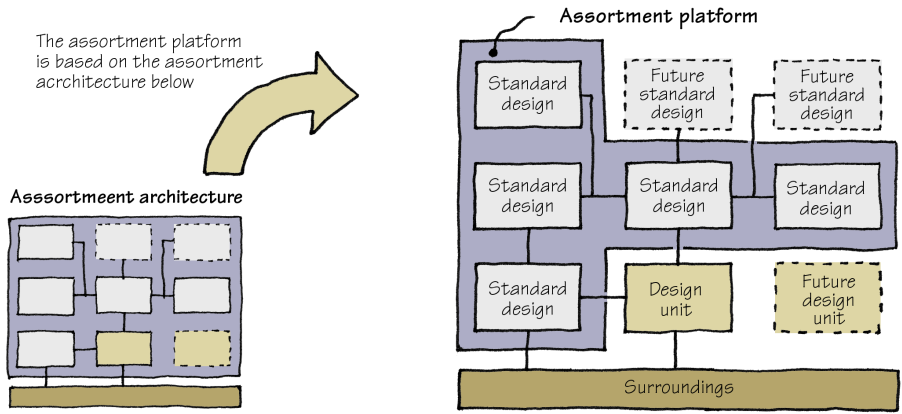


Figure 44. Symbolic representation of an assortment platform that is based on the assortment architecture illustrated in Figure 41.

Definition of an assortment platform

An assortment platform is a platform that covers a product assortment. An assortment platform is constituted by existing standard designs, interfaces among standard designs, interfaces among standard designs and design units and interfaces among standard designs and/or the surroundings.

Family platform

A family platform is the subset of an architecture that applies for a product family and meets with the general platform definition.

The symbolic representation of a family platform in Figure 45 is based on the assortment platform illustrated in Figure 44. Other family platforms could be derived from the same assortment platform.

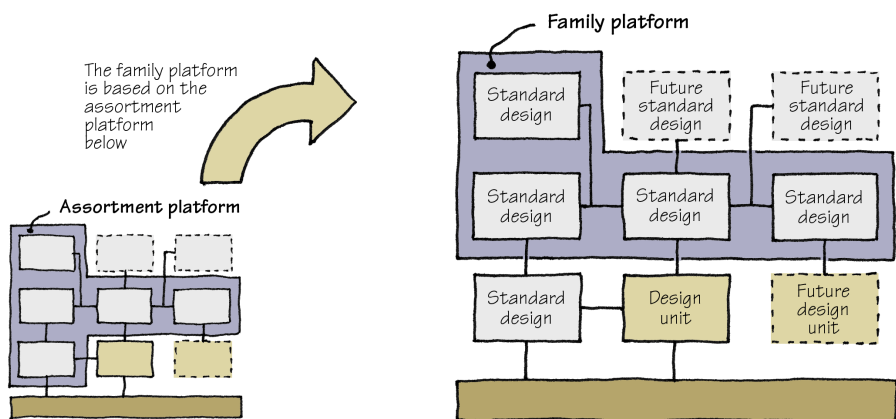


Figure 45. Symbolic representation of a family platform that is based on the assortment platform illustrated in Figure 44.

Definition of a family platform

A family platform is a platform that covers a product family. A family platform is constituted by existing standard designs, interfaces among standard designs, interfaces among standard designs and design units and interfaces among standard designs and/or the surroundings.

Product platform

The term product platform is needed for pinpointing the part of a product that is re-used across several products, product families or the entire product assortment. The term platform is the totality of what is re-used. This totality again consists of standard designs.

A product platform is the subset of an architecture that applies for a single product and meets with the general platform definition.

The symbolic representation of a product platform in Figure 46 is based on the family platform illustrated in Figure 45. Other product platforms could be derived from the same family platform.

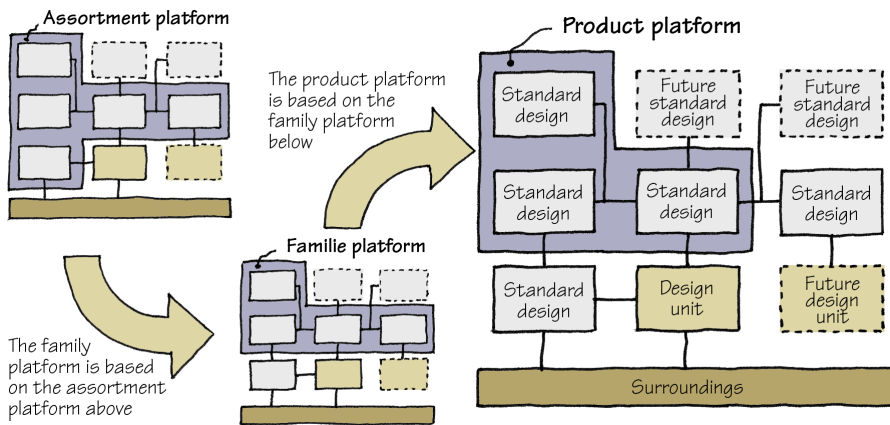


Figure 46. Symbolic representation of a product platform that is based on the family platform illustrated in Figure 45.

Definition of a product platform

A product platform is a platform that covers one individual product. A product platform is constituted by existing standard designs, interfaces among standard designs, interfaces among standard designs and design units and interfaces among standard designs and/or the surroundings.

11.4 Ownership of interfaces

This research includes the interfaces as part of the definitions of architecture, platform and standard design. This implies that models of architecture, platform and standard design will all include interfaces. Application of such models might lead to confusion on who has the responsibility and ownership of the interfaces, as these are specified, developed, documented and maintained. Three approaches seem applicable:

- *The owner of the architecture owns the interfaces* – One approach is to appoint the ownership and the responsibility of the interfaces to the owner of the architecture. This approach is obvious as the objective of the architecture is to manage the development of product families and standard designs.
- *The owner of the standard design owns the interfaces* – A second approach is to let the owner of the standard design have responsibility of the interfaces. These people are the people that daily work with the interfaces. The disadvantage of this approach is that the ownership of the interfaces will be shared among the owners of the standard designs. Example: A power supply standard design interfaces with several other standard designs. Consequently, the ownership of the interfaces is distributed among all these standard designs.
- *Each interface is appointed an owner* – The third approach is to appoint one owner to each interface. This ownership is independent of the owners of the standard designs and the architectures. These people have the responsibility of specifying, developing, documenting and maintaining the interfaces in agreement with the architecture and standard design.

From a dialogue with Philips Consumer Electronics it is learned that they have applied the third approach. Their motivations are that the interfaces exist longer than the standard designs and lot of effort is put into designing the interfaces, e.g. software protocols. At Bang & Olufsen they have chosen to apply the second approach because the ownership of the architecture is not clearly defined yet and because the responsibility for the standard designs is clearly defined. This research does not conclude on what approach to apply. It depends on the organisation.

11.5 Recursive phenomena

The phenomena of architecture, platform, standard design and design unit are recursive, meaning that the phenomena can repeat themselves, e.g. a standard design can consist of "smaller" standard designs. Another example could be that a standard design might have its own architecture, if it complies with the above definitions.

MILLER 2001 shows that the phenomena of structures and modules are recursive in an example from a biotech plant (Figure 47). The plant is hierarchically structured in accordance with the process units used in production of biotech products. The highest level "1" denoted the whole plant. The next level "2" denoted process unit modules that match process units in production. At the next level "3" are equipment modules, i.e. vessels and tanks equipped with components to possess full functionality. At the lowest level "4" are components like valves and flow meters.

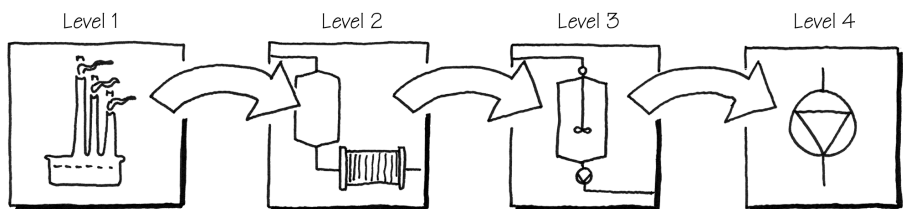


Figure 47. An example of a recursive structure and modules for architecture and standard designs. The example has its origin in a biotech plant, after MILLER 2001.

11.6 Architecture and platform for life phase systems

Definitions of architecture, platform, standard design and design unit are proposed with Bang & Olufsen products in mind. These products are televisions, loudspeakers, music systems, phones, etc. Such products are mechatronic, i.e. mechanics, electronics and software. Experiences from Bang & Olufsen show that all three subject areas are present as architecture, platform, standard design and design unit are described.

From projects in the production area at LEGO (manufacturer of plastic toys), it is learned that application of platform thinking is just as powerful in the production area as it is in the development area. One of the challenges with a product assortment is the growing number of variants. Analogous to this, the production area has a challenge of a growing number of variants of production equipment. The variety of equipment is often growing in order to meet the variety of the product assortment. One way to deal with this variety is to develop the equipment based on a platform. LEGO has with success developed a part of their injection mould assortment as a platform. Larger parts of the moulds have been standardised, but the parts that form the LEGO bricks are not standardised.

The LEGO case shows that the vocabulary formulated above seems valid also for equipment in the production areas. It is therefore concluded that the vocabulary is also valid for equipment in life phase systems.

11.7 Architecture and platform alignment

From the Theory of dispositions (Page 36) it is learned that decisions made in one area influence (dispose) the type and efficiency of the operation in another area. The Theory of dispositions sees dispositions as the mechanism behind all DFX areas and efforts, OLESEN 1992.

Figure 48 shows the general model of the “fitting” of a product structure and an assembly system structure. When this fitting is obtained, an alignment is established for the actual life system architectures. Observe that the alignment is mutual as known from the DFX area: both DFA and AFD (Assembly for Design) can be established, ANDREASEN & MORTENSEN 1997. Successful applications of platforms show that this alignment is essential.

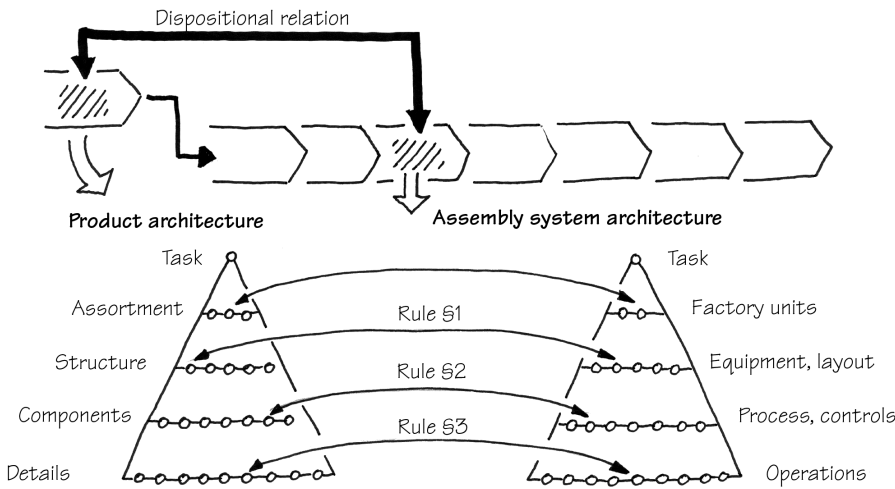


Figure 48. A dispositional relation leads to rule-based alignment between the architecture and the architecture of a system, e.g. assembly system, ANDREASEN ET AL. 2004.

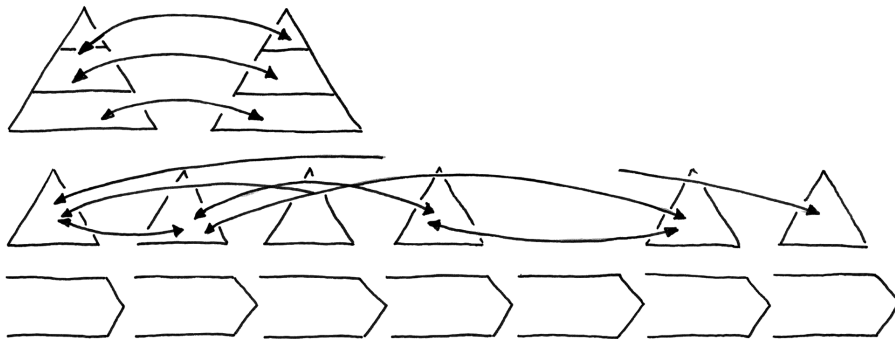


Figure 49. Alignment of architectures with life phase systems can be done for an assortment, family and product, ANDREASEN ET AL. 2004.

The dispositional alignment of architectures shall not only be seen as alignment of products and standard designs, but also as alignment with other life phase systems. It is previously stated that architectures can be identified for products on different levels, i.e. assortment, family and product architectures. Likewise, for the life phase systems. There might exist architectures on different levels for the injection moulds at LEGO, i.e. assortment, family and individual injection mould. Alignment of these architectures can be done on all three levels as illustrated in Figure 49.

12 Relation to other research contributions

The above chapter contributes to a vocabulary for architectures based on artefact theories, e.g. the Theory of technical systems. The following chapter describes how these contributions add to and/or differ from other research contributions the phenomena.

12.1 Relation to other definitions of design unit, standard design and module

The concepts of design unit, standard design and module are introduced as the building blocks for architectures and platforms. The concept of design units is inspired by MORTENSEN & ANDREASEN 1996 as a concept for encapsulation of functions, organs and parts. The design unit serves the purpose of encapsulating a part of the design into manageable units for the purpose of designing and modelling.

Design units that are used in more than one product are denoted standard designs. This term is inspired by Philips Consumer Electronics, NIEUWLAND 1999. The concept of module sticks to the definition provided by ERICSSON & ERIXON 1999.

The contributions from this research on these concepts are related to their application in the context of architecture and platform design:

- *Re-use vs. no re-use* – The distinction between design units and standard designs are included in this research in order to distinguish clearly between the units that are re-used and those that are not re-used. None of the publications on this topic include this distinction. However, there exist publications on modelling architectures that to some extent illustrate such distinction, e.g. SUDJANTO & OTTO 2001.
- *Rules* – A central part of the definition of standard design is the formulation of the three rules that legalise the appointment of a design unit to be a standard design. These rules are "Decision of re-use", "Documentation" and "Responsibility". The rules are introduced to emphasise the importance of conscious management of the elements of architectures and platforms.
- *Abstract* – In order to enable re-use of design units from one product to another the definition suggests that standard designs can be re-used on different levels. This implies that what is re-used is not necessarily the physical solution, but could just as well be a diagram, specification, etc.

The concepts of design unit, standard design and module that are introduced in this research enable comprehensive definitions of architecture and platforms.

12.2 Relation to other definitions of architecture

Normally, the word architecture is used as a synonym for structure, influenced by American literature. Part 2 (Page 41) includes a review of literature published related to architecture. The dominant authors are:

- *ULRICH 1995* – This definition claims that an architecture is constituted by functional structures, mapping between functions and parts and interfaces. Further description of this definition is found in “Product architecture” (Page 54).
- *SANCHEZ 2000A* – *SANCHEZ 1999B* argues that a product architecture consists of functional components and a full specification of how the individual components interact with each other. Furthermore, *SANCHEZ 2000A* & *MILLER 2001* introduces the existence of process and knowledge architectures. Further description of these definitions is found in “Strategic modularisation by using product, process and knowledge architectures” (Page 55).
- *MOORE ET AL. 1999* – “*The product architecture is the plan for how a variant will be split into modules and how those will interface with one another*” *MOORE ET AL. 1999*. Hereby, the architecture concept is linked to modules.
- *Philips Consumer Electronics* – *PHILIPS 2000* states that an architecture describes how a product family is decomposed into subsystems/components. Furthermore, the architecture includes the interfaces within the architecture and the interfaces with the surroundings. Finally, the architecture is described by a set of guidelines for application of the architecture. Further description of these definitions is found in “Case: Philips Consumer Electronics” (Page 47).

The above summarises the key lessons learned from the dominant authors. The following includes aspects, where the results of this research differ from previous publications (Page 41):

Structure and the structural elements – The definition of architecture formulated in this research complies with the above definitions in the sense that an architecture is a structure of a product or a product family. In this research the elements of an architecture are standard designs, design units and interfaces. Hereby, this research differs in the sense that the key elements of the architecture are standard designs and design units, whereas other authors focus on function, components and subsystems. The distinction between standard design and design units pin points the difference between units that are re-used (i.e. standard designs) and units that are not re-used (i.e. design units).

Time perspective – The definition of architecture includes the key elements standard designs and design units. It is noticed that this definition distinguishes between future standard designs, existing standard designs, future design units and existing design units. The reason for this distinction is to ensure that the architecture is valid for products currently on the market as well as products to be launched in the future. This timing aspect is not treated by other authors in the reviewed literature.

Interfaces – A central point for all definitions of architectures are the interfaces. It is often emphasised how important these are. These interfaces are among the elements of the architecture. *PHILIPS 2000* suggests that interfaces with the environment are part of the definition as well. By environment, *PHILIPS 2000* means the standard designs and other elements of the product (i.e. design units). This research denotes these interfaces as the interfaces

among the standard designs and design units. The definitions in this research also propose interfaces with the surroundings. These interfaces are the interfaces between the elements of the architecture and external surroundings such as other products.

Variety – One of the motivations for introducing architectures is the ability to deal with variety. The concept of variety formulated in this research deals with variety by means of combining future standard designs, existing standard designs, future design units and existing design units differently. Also, the variety is enabled by having variants of the individual units.

Levels – The definition of architecture suggests that architectures exist for product assortments, product families and individual products, respectively.

Rules of existence – An architecture is based on standard designs. This implies that a product, product family or product assortment does not have an architecture unless standard designs exist that comply with the definition of a standard design.

Activity architecture – The definition of architecture formulated in this research does not include the types of architecture that are denoted activity architectures as described by SANCHEZ 1999B and MILLER 2001. It is not argued that such activity architectures do not exist, but it has not been within the scope of this research to investigate this aspect. In this research it is argued that architecture is applicable for life phase systems that share the characteristics of a product, e.g. production equipment.

Knowledge architecture – The formulation of architecture does not comply with SANCHEZ 1999B's and MILLER 2001's concept of knowledge architecture. The existence of such architectures has not been discussed in this research, as it is outside the scope of this research.

12.3 Relation to other definitions of platform

The general understanding of a platform is that it is the set of components and subsystems shared across multiple products, GONZALES-ZUGASTI & OTTO 2000. Other authors add slight differences to this conception.

- *Platforms based on common modules* – ERICSSON & ERIXON 1999 link the term platform to modules by stating that a platform refers to a common base from which a number of preferred models are built.
- *Platforms based on common technology* – The term technology is often referred to in relation to platforms. MAIER & FADE 2001 argue that a product platform refers to a common technology from which a product family is derived. Likewise, McGRATH 2001 and SIDDIQUE ET AL. 1998 state that a product platform is the lowest common denominator of relevant technology in a set of products.
- *Platforms based on common assets* – It is by some authors argued that platforms are a collection of assets that are shared by a set of products. Such assets are components, processes, knowledge, people and relationship among people. Some of the authors who promote this approach are ROBERTSON & ULRICH 1998 and KRISTJANSSON ET AL. 2004.
- *Platform includes interfaces* – MEYER & LEHNERD 1997 include the term interfaces in the definition of a platform by stating that a product platform is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced. Likewise, SAWHNEY 1998 argues that a platform is the

set of elements and interfaces that are common to a family of products.

- *Platform includes structures* – MEYER & LEHNERD 1997 also include structure as a part of the platform definitions, as they state that “A platform is a set of subsystems and interfaces that form a common structure...” MEYER & LEHNERD 1997

From time to time is difficult to see the difference between an architecture and a platform in the literature. Both concepts refer to structure, interfaces, re-use and modules.

The concept of a platform formulated in this research has its starting point in the definition of an architecture. It is stated that a platform is an instance of an architecture that only includes existing standard designs and their interfaces. This approach differs from others authors by:

Coherence – One of the differences promoted in this work is the coherence between the definition of architecture and platform. A platform is a subpart of an architecture. This implies that a platform does not exist unless a clearly defined architecture and standard designs exist.

Existing standard designs – The platform definition states that a platform consists of the standard designs that at a given time are implemented. Consequently, a platform consists only of the elements that are re-used at the moment and not elements that will be used in the future.

Abstractions – A standard design can by definition have different physical implementations. This implies that the physics of the common elements of the platform is not necessarily identical, even though it is based on the same standard design.

Interfaces – As the definition of a platform is based on the definition of an architecture, it implies that the interfaces are also part of the platform definition. Normally, this is taken for granted as the traditional definitions include physical systems/components.

12.4 Comparing the vocabulary with other research contributions on architecture and platform

The state-of-the-art chapters (Part 2) showed a number of authors and companies who have contributed to the research community on the topic of developing product families based on architectures. Table 4 (Part 2, Page 71) classifies their contributions. The contributions are in Table 5 classified again. This time the classification reflects to what extent they contribute to the aspects of architecture and standard design treated in this research.

The top column in Table 5 includes the elements of the vocabulary proposed in Part 3. The left row lists the authors from “State-of-the-art: Studies on research theories related to development of product families” (Page 54). The dots show how the authors are related to the elements of the vocabulary proposed in Part 3.

Phenomena Contribution															
	Design unit & standard designs	Re-usable vs. non re-usable	Future vs. existing	Interfaces among design units	Interfaces with surroundings	Application characteristics	Architecture	Elements (designs units & standard design)	Interfaces among design units	Interfaces with surroundings	Assortment architecture	Family architecture	Product architecture	Application characteristics	Platform
Product architecture, Page 58															
Ulrich 1995									⊕				⊕		
Ulrich & Eppinger 2004				⊕				⊕					⊕		
Strategic modularisation by using product, process and knowledge architectures, Page 59															
Sanchez 1999b				⊕								⊕	⊕		
Sanchez 1999a				⊕								⊕	⊕		
Sanchez & Collins 2001													⊕		
Sanchez 2000a				⊕						⊕		⊕	⊕		
The power tower, Page 60															
Meyer & Lehnerd 1997															⊕
Factors influencing a platform strategy, Page 63															
Kristjansson & Hildre 2004		⊕													⊕
Kristjansson et al. 2004		⊕										⊕			⊕
Functional structures as a basis for modularisation, Page 64															
Zamirowski & Otto 1999				⊕				⊕					⊕		
Sudjianto & Otto 2001				⊕				⊕					⊕		⊕
Design structure matrix, Page 65															
Pimmler & Eppinger 1994				⊕									⊕		
Baldwin & Clark 2000				⊕									⊕		
Design for variety, Page 67															
Erens 1996											⊕				
Baukasten system, Page 68															
Borowski 1961		⊕													
Module drivers, Page 69															
Erixon 1998		⊕													
Ericsson & Erixon 1999		⊕													
Modular function deployment, Page 70															
Erixon 1998				⊕									⊕		
Ericsson & Erixon 1999				⊕									⊕		
Aligning modularisation, Page 71															
Pulkkinen 2000		⊕													⊕
Pulkkinen et al. 2003		⊕													⊕
Pulkkinen et al. 2004		⊕													⊕
Modular engineering, Page 73															
Andreasen 1998		⊕													
Miller 2001		⊕			⊕										
Contributions from this research	⊕	⊕	⊕	⊕	⊕			⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕

Table 5. Mapping research contributions to the vocabulary: the top column includes the elements of the vocabulary. The left row lists the authors from "State-of-the-art: Studies on research theories related to development of product families" (Page 54). The dots show how the authors are related to the elements of the vocabulary proposed in Part 3.

Verification of hypotheses

The objective of Part 3 has been to formulate a vocabulary, which contributes to artefact theories, e.g. the Theory of technical systems. The contribution should extend these theories to be valid for product families. Two hypotheses have been sought verified. The hypothesis no. 1 and 2 respectively argue for the existence of architectures and standard designs. Throughout Part 3 the concepts of architecture and standard design are detailed, which is done in agreement with hypothesis no. 1 and 2.

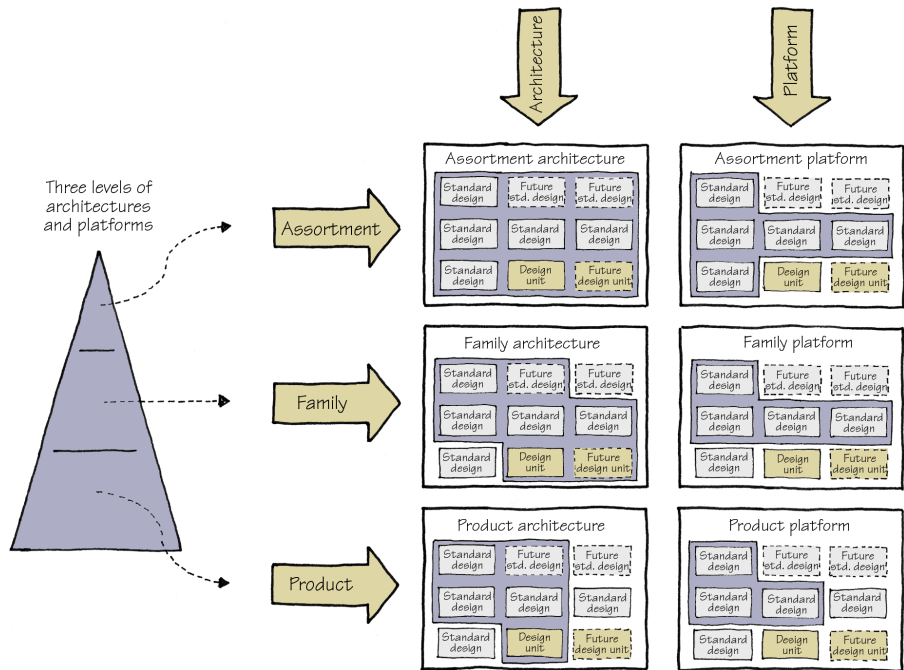


Figure 50. Overview of vocabulary and the relations between the terms existing design unit, future design unit, existing standard design, future standard design, module, interface, architecture, assortment architecture, family architecture, product architecture, platform, assortment platform, family platform, product platform, architecture alignment and platform alignment.

It is shown that it is possible to formulate a vocabulary, which has the concept of architecture as the core structure. The structure describes the building principles of product families. A central element of the architecture concept is the standard design, design unit and interface. The concept of standard design is defined in Part 3. The concept of standard design is described by its elements (i.e. interfaces, parts, organs, etc.) and when to denote a design solution a standard design. It is shown that it is possible to apply the concept of standard design to encapsulate, document and manage the design entities that are re-used within product families.

Based on the successful formulation of the vocabulary it is concluded that Part 3 verifies hypotheses no. 1 and no. 2. Modelling concepts of architecture and standard design is treated in Part 4. Part 5 includes examples of industrial applications. Later chapters will therefore conclude on the usefulness of the concepts formulated in Part 3.

Part 4

Supporting tools for developing architectures for product families

Part 4 introduces two tools that can be applied for modelling standard designs, architectures and product families. The first tool is denoted "Generic organ diagram". It aims at modelling the structure and interfaces of architectures. The second tool is denoted "Product family master plan" (PFMP). The PFMP aims at modelling product families and especially variety of product families.

Part 4 focuses on modelling of standard designs, architectures and product families. One of the basic assumptions for this research is that explicit and visual models enable better decision making regarding development of product families (Page 18). Consequently, models of architectures, standard designs, etc. can lead to better decision making regarding the objects e.g. standard design.

According to the earlier definitions of architecture, a model of an architecture includes existing standard designs, existing design units, future standard design and/or future design units. The architecture also includes interfaces among the units and interfaces with the surroundings. Likewise a model of a platform includes existing standard designs, interfaces among standard designs, interfaces among standard designs and design unit and/or interfaces among standard designs and the surroundings. From a modelling point of view there is no difference between architectures and platforms except from what is highlighted in the previous chapters. Therefore, there is not distinguished between architectures and platforms in the models to follow.

Four aspects are essential to model when designing or managing standard designs, architectures and product families:

- *Organ structure* – Design units and standard designs consist of organs. The starting point for identification of standard designs is the organs used in several products or product families. It is therefore essential to be able to model the organs and their structure when design units and standard designs are identified. A model of a product family's organ structure should show the structure and the variety of organs.
- *Organ interfaces* – One of the fundamental elements of successful re-use of standard designs is standardisation of interfaces. This is also emphasised in the definitions of standard design and architecture. A model of an organ structure should therefore provide an overview of the interfaces among the organs. Such an overview is essential for identification of interfaces to be standardised.
- *Visualise variety* – A product family or assortment should provide variety towards the market to ensure that the customer gets the right product. At the same time the product family or assortment should have a high degree of re-use. Decisions regarding a product family can benefit from an overview of the variety within the product family. An overview that describes the product family or assortment from commercial, functional and physical points of view.
- *Linking the variety* – An overview of a product family or assortment that describes the variety should also describe how commercial, functional and physical variety are related.

The above aspects are some of the aspects that have to be considered as architectures and product families are designed or managed. Other aspects related to modelling of architectures and product families are of importance, such as market application, behaviour, cost, etc. However, the scope of this research is limited to the above aspects.

Structure of Part 4 – Part 4 proposes two supporting tools for modelling architectures, standard designs and product families. The first tool introduced focuses on modelling the organ structure and the interfaces of the organs. This tool is denoted *Generic organ diagram*. The generic organ diagram is intended for modelling architectures and standard designs. Modelling of architectures and standard designs are needed in the design process as well as for the final documentation of the concepts. The second tool introduced focuses on modelling the variety of features, organs and components within a product family. This tool is denoted *Product family master plan* (PFMP). PFMP can be applied for modelling product families that have thousands or even millions of product variants. Throughout Part 4 a number of examples are included. But the real industrial applications are described in Part 5.

14 Tool: Generic organ diagram

The following proposes an approach for modelling architectures from a functional point of view by means of organs. Many authors in the field of architecture emphasise functional modelling as a basis for defining architectures, SUDJANTO & OTTO 2001, ULRICH 1995, etc.

According to the definition of an architecture proposed in this research, an organ model of a product family is not considered an architecture in itself, but it is included in this research because it is seen as essential for identification of standard designs and architectures and because few authors show how such modelling is done.

The approach formulated here has its starting point in the Theory of technical systems (HUBKA 1973) and the Theory of domains (ANDREASEN 1980). The functional structures that are proposed by authors in the field of architectures are denoted organ structures according to the Theory of domains (e.g. ANDREASEN 1980 and MORTENSEN 2000). This research keeps the notion organ structures.

The chapter is structured by introducing a modelling formalism. The formalism is denoted *Generic organ diagram*. After introducing the modelling formalism, an example from Bang & Olufsen is presented.

14.1 Model: Organs and organ interfaces

The proposed modelling approach follows the modelling approach that is typically applied for modelling architecture, e.g. SUDJANTO & OTTO 2001, ULRICH 1995, etc. A block diagrams is utilised (Figure 51). Each block in the diagram represents an organ or a group of organs. The interfaces between the organs are drawn with lines that connect the organs.

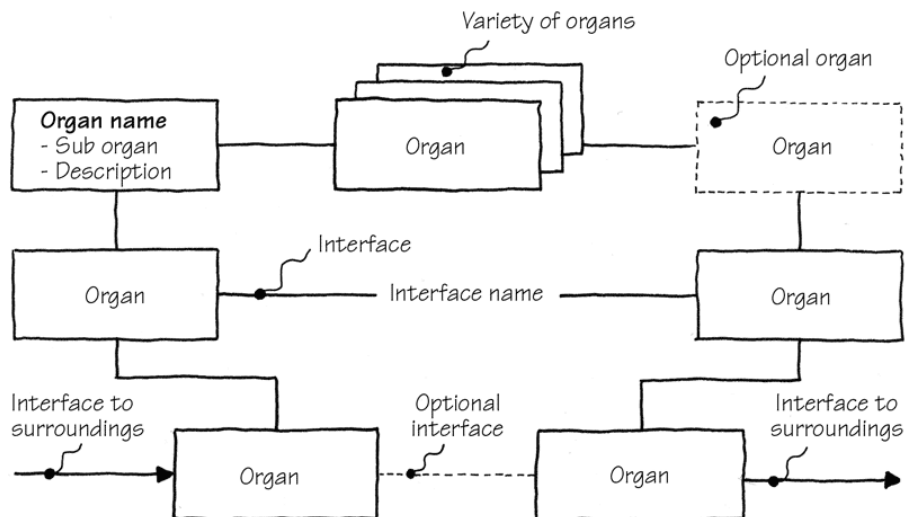


Figure 51. Symbolic representation of a generic organ diagram. This notation is applied for all models of architectures, standard designs and platforms in this research.

Figure 51 includes a symbolic representation of a generic organ diagram. Each block represents an organ or an encapsulation of organs. Each block is given a name. Below the name a small description of the organ can be written and the sub organs can be included. Instead of a description, it is also an option to list features or functions. Such details might seem unnecessary at the time when the model is drawn. However, experiences from Bang & Olufsen show that descriptions are of importance, as the model is used for communication of the structure in the organisation. For instance, if a block represents a microprocessor, it is often necessary to state, what microprocessor is chosen and what key functionalities provides. Different microprocessors offer different functionalities and if the microprocessor is changed, it might cause radical changes in the standard design due to missing or additional functionalities in the new microprocessor.

An architecture is typically applied for modelling different product variants. Product variety

related to variety of organs should be reflected in the generic organ diagram. Therefore, organs that vary are represented by blocks that are staggered behind each other (Figure 51). An example could be a hard drive in a television, which is offered with 200, 250 or 300 GB capacity. Organs that are not always included in the product, i.e. organs that are optional are marked with dotted lines (Figure 51).

The structure of the generic organ diagram appears as the relations are added to the model. In this case the relations are the interfaces among the organs. The interfaces between organs are drawn with lines that connect the blocks (Figure 51). PIMMLER & EPPINGER 1994 define four classes of interfaces: spatial, energy, information and materials. In a formal generic organ diagram each interface is given a name that is written next to the interface line (Figure 51). In case of electronics an interface between two blocks is typically a group of connections, but these are all represented in one single line for power, one single line for signal, etc. If further descriptions of the interfaces are needed, such are documented elsewhere.

The definitions of architecture from previous chapters emphasise the importance of interfaces with the surroundings (Architecture, Page 81). Such interfaces are drawn by means of interface lines that point in the direction in or out of the model (Figure 51). Interfaces that not always exist are marked with dotted lines, which for instance would be in case of optional organs (Figure 51).

A generic organ diagram is typically read from the left to the right following the interfaces. This is typically possible for models that represent products that process objects, e.g. a television processes a TV-signal to an image, a car engine processes gasoline to a rotation, etc. It is, however not always possible to follow the “left to right rule” and in such case it is up to the user to find a suitable “flow” in the model.

The formalism described above is applicable for single products and product families. At Bang & Olufsen the model has been applied for analysis of the organ structures as well as for synthesis of new products. The following includes an example where the formalism has been applied for studying functional commonality among six loudspeaker families at Bang & Olufsen.

14.2 An example of application: Loudspeaker families

One of the first initiatives carried out at Bang & Olufsen in the process of introducing architectures and standard designs was a project to investigate if re-use could be an option from a technical point of view, PLOUG 1999^B and PLOUG 1999^A. The objective of introducing this case in this part of the research is to illustrate how the modelling formalism described in the above has been applied.

This project was carried out for loudspeaker families BeoLab 2000, 2500, 3500, 4000, 6000 and 8000 (Figure 52). These loudspeaker families are all commercial successes as they have been well adapted by the market and they have low call back rates.

The individual loudspeaker families were developed in “isolated” projects in the period 1991 to 1997 (Figure 52). In these projects there was no re-use from one product family to another. Consequently, the individual loudspeaker projects utilise state-of-the-art technologies. The engineers’ desire to make even better solutions led to no re-use from one loudspeaker family to another. LUND & KRISTENSEN 2000 state that commonality and re-use has not been a part of the “development mindset” at Bang & Olufsen in this period.

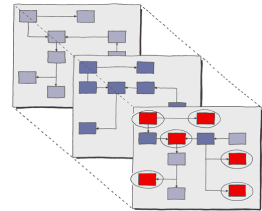


Figure 55. Each organ diagram is printed on overhead slides. By putting the slides on top of each other, it is possible to compare the organs between two loudspeaker families. Left: Includes a subset of two overheads where are placed on top of each other. Right: Principle illustration of “overlap” between the organ structures.

The diagram illustrates a complex home theater system architecture. At the center is a **Microprocessor** unit, which is the hub for most control and data flow. It is connected to a **DSP** (Digital Signal Processor) and an **ICEPower** amplifier. The **ICEPower** amplifier is further connected to a **Varme** (Heat) source and a **Diskanthyl** (Diskant) source. The system also includes a **Master Link Plug**, a **Keyboard**, a **Display**, a **Status Indicator for time**, a **Stand-by indicator**, a **Netlag**, a **Netbusling**, a **Relay**, and a **Stand-by SMPS** (Switching Mode Power Supply). The diagram is color-coded and includes various labels for components and their connections.

Figure 56. A draft of a generic organ diagram for a family architecture. The model is a proposal for a family architecture that would have enhanced re-use among the six product families.

The loudspeaker case is further documented in HARLOU 2000A and a similar case for temperature sensors is documented in HARLOU 2000B.

14.3 Conclusion on modelling organ structures

Chapter 14 introduces a modelling formalism for modelling organs and organ structures. The tool is denoted *Generic organ diagram*. The generic organ diagram enables modelling of organs and variety of organs within a product family or several product families. Variety is presented either as an organ that is an option (e.g. a computer with or without a DVD-drive) or as an organ that exists in different version (e.g. a hard drive with 200, 250 or 300 GB capacity).

The generic organ diagram is intended for comparing products or product families. Such comparison may form basis for identification of standard designs and architectures. The modelling formalism is also intended for modelling standard designs and architectures. Such models can be applied in the design process or as a part of the final documentation of the standard designs and architectures. Part 5 includes examples of applications of generic organ diagrams at Bang & Olufsen and Vestas.

15 Tool: Product family master plan

As a product family is developed or re-designed it is crucial to have an overview of the variety within the product family. A product family might include thousands or even millions of variants. It can be an extensive task to describe all these individual product variants. However, the overview is essential as decisions have to be made concerning the existence of each individual variant.

Two situations are important to support. The first situation is when a company is starting to consider the application of platforms and architectures. In this situation the existing product families and assortment will play an important role for identification of the new standard designs and architectures. It is therefore of high importance to be able to describe the existing product assortment. The second situation is when new standard designs and architectures are developed. In this situation it is relevant to be able to describe what this standard design or architecture should be able to do, i.e. what variants can be derived from the standard designs and architectures.

Such an overview of a product family should describe the structure of the product family and the variety within the product family. According to ANDREASEN ET AL. 1996 ("Multiple structures" Page 33) several viewpoints are needed to describe a product or a product family. Three of the viewpoints that are of interest when modelling a product family, are:

- *Customer view* – A customer view should describe the product family from a customer's point of view. This implies that it should show the variety from a market point of view. The customer view should bring an answer to the question "What are the features and application characteristics that have the customer's interest?"
- *Engineering view* – An engineering view should describe the product from an engineering point of view. This implies that it should describe the organ structure of the product family and the variety of organs. It should hereby answer the questions "How does the product family work and how does it vary from an organ point of view?"
- *Part view* – A part view should describe the physical entities of the product family and hereby bring answers to questions "How is the product family realised physically and how does it vary from a physical point of view?"

Figure 57 illustrates a principle model of a product family, which includes the three views. The three views are related in the sense that the product family (i.e. the engineering view) should show variety to the markets (i.e. the customer view) and commonality to the production system (i.e. the part view).

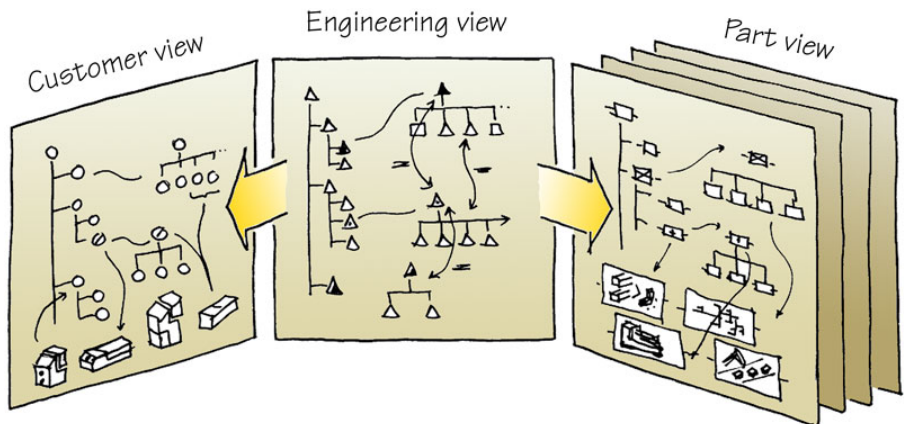


Figure 57. Three aspects are of interest when modelling variety of a product family. These are customer, engineering and part views.

An overview of a product family, which includes the three views, should enable a company to make better decisions regarding the product family and the variety of the product family. Such decisions concern reduction of non-value-adding variety, identification of standard designs, etc.

The objective of this chapter is to contribute to a formalism for modelling product families with a high degree of variety. The modelling formalism is denoted *Product family master plan (PFMP)*. The chapter is structured by introducing a modelling formalism known from software programming. This is followed by the general PFMP formalism. After the introduction of the general PFMP formalism the customer, engineering and part views are treated separately. The three views are followed by a description of how the views are related to each other and how such relations are represented with a PFMP. Finally, an example of application of the PFMP formalism is presented.

15.1 Basic modelling formalism

The basic modelling formalism, which is applied for modelling a product family in a PFMP, has its origin in the object-oriented paradigm and system modelling. These are introduced in the following.

System modelling

One of the first things to consider when modelling a product family, is to determine the borderlines of the product family to be modelled. Example: Is accessories, software, manuals, etc. included in the model? Also, one should make clear whether all variants of the product family should be included in the model. It might seem naive to go through such considerations. Never-the-less, one has to make decisions about these issues.

The concept of system modelling (System theory, KLIR & VALACH 1965) provides assistance

for identification of what belongs to the model and what should be outside the model. In system modelling, objects are modelled as a set of elements and relations (Figure 58). The system has a boundary that separates the system from the environment. From the environment inputs are received and outputs are delivered to the environment.

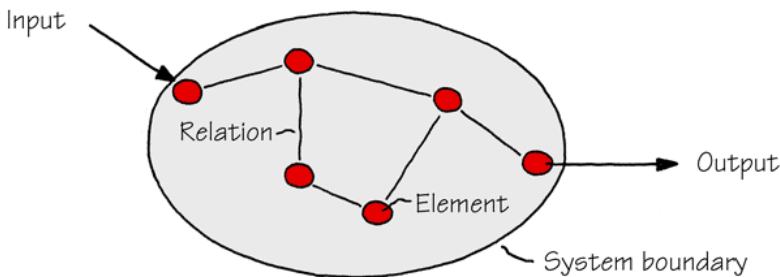


Figure 58. Principle drawing of a system including elements, relations, inputs, outputs and a system boundary.

Example – The elements of a car family is the different engines, transmissions, wheels, roofs, hoods, etc. The relations are of space and effect nature. The position of the four wheels in each corner of the car chassis is an example of a space relation. An example of an effect relation is that the transmission receives a rotary motion from the engine. The input to the car system could be gasoline and the output is the emissions from the fuel combustion.

HABERFELLNER ET AL. 1994 and KLIR & VALACH 1965 argue that two types of attributes are relevant when applying system modelling. These are the structural and the behavioural attributes. Structure describes how the system is built up and answers to the question “What is it?” Behaviour is the relation between input and output and answers to the question “What is it able to do?” The structure of a dog is that it has four legs, one head, one heart, etc. The behaviour of the dog is that it eats, runs and maybe bites. The distinction between structure and behaviour is relevant because only the structure can be determined directly during configuration and design, whereas behaviour is determined by structure and input from the environment. Determining structure and behaviour is a means for identification of what parameters the user can influence directly and what aspects that cannot be influenced.

The object-oriented paradigm

The object-oriented paradigm is a modelling formalism that is applied for development of software. The object-oriented paradigm has proven to be beneficial for encapsulating software building blocks into classes (i.e. modules) that can be re-use. The formalism applied in the object-oriented paradigm has proven to be powerful for visualising software architectures.

The formalism is introduced in this research because the formalism can be applied for modelling product families, if the formalism is combined with the Theory of technical systems and the Theory of domains. The key elements of the object-oriented paradigm are objects, classes, attributes and instances. These are defined in the literature as:

- *Object* – “An abstraction of something in a problem domain, reflecting the capabilities of a system to keep information about, interact with it or both; an encapsulation of attributes values an their exclusive services” COAD & YOURDON 1991 “An object has state, behaviour and identity...” BOOCK 1991.

- *Class* – “A class is a set of objects that share a common structure and a common behaviour” BOOCK 1991.
- *Attribute* – “Any property, quality, or characteristic that can be ascribed to a person or thing” COAD & YOURDON 1991.
- *Instance* – “An instance is a specific object. Therefore an instance is an object with state, behaviour and identity” COAD & YOURDON 1991.

Three different relations can exist between elements in the object-oriented paradigm. These are generalisation-specialisation connections, whole-part connections and instance connections. These are illustrated in Figure 59.

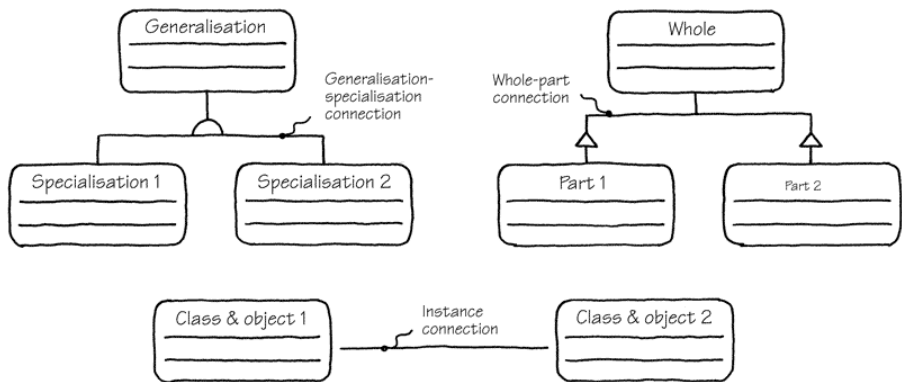


Figure 59. Notation for connections applied in the object-oriented paradigm, COAD & YOURDON 1991. The connections can be of the type generalisation-specialisation connections, whole-part connections and instance connections.

The tree types of relations are defined in the literature as follows:

- *Generalisation-specialisation connection* – The generalisation-specialisation connection is the mechanism, which delegates characteristics from one object to another object (specialisation), COAD & YOURDON 1991. For instance the class *car* is a generalisation of the class *sports car*. Generalisation-specialisation connection is in the literature also named *kind-of connection* or *inheritance*.
- *Whole-part connection* – A whole-part connection is a relation between at least two objects. One object (whole) is connected to one or more objects (parts) – saying that the whole object consists of a number of part objects, COAD & YOURDON 1991. For instance the class *car* consists of the class *wheels*. The whole-part connection is in the literature also named *part-of connection* or *aggregation*.
- *Instance connection* – “An instance connection is a model of problem domain mapping(s) that one object needs with other objects, in order to fulfil its responsibilities” COAD & YOURDON 1991.

The object-oriented paradigm and its notation will in the following sections be applied for modelling product families. The object-oriented paradigm is not a theory that describes products or product families. Therefore, the object-oriented formalism does not in itself describe how to model a product family. Later sections combine the object-oriented formalism with System modelling, Theory of technical systems and the Theory of domains. This

enables the formulation of a tool for modelling product families, i.e. PFMP.

15.2 The basic PFMP modelling formalism

With the introduction of the basic concepts of System modelling and Object-oriented modelling the PFMP modelling formalism can be introduced. The PFMP formalism was introduced by HARLOU & NIELSEN 1999 and later detailed by MORTENSEN 2000 and MORTENSEN 2001. The following describes the concepts further.

Three types of elements constitute the PFMP modelling formalism: classes, attributes and constraints. Besides these elements a PFMP consists of two types of structures. These structures are denoted part-of and kind-of structures. They are described in the following.

A small example of a PFMP for a car family

Before going into details with all the modelling aspects that are included in a PFMP, the concept of PFMP is described by a small example. The extract of a PFMP in Figure 60 illustrates a model of several car families. Reading from the top left corner of Figure 60, the car family is defined. Following the line to the right the different car models are listed (Sedan, Station wagon and Van).

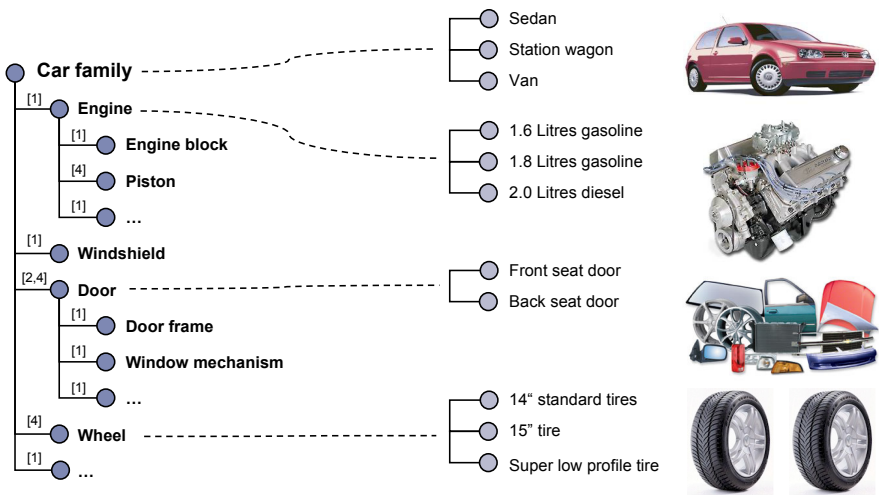


Figure 60. A small example of a PFMP that describes three car families.

Again, reading from the top left corner of Figure 60 the parts of the car are listed. The car consists of one engine, one windshield, two or four doors, four wheels, etc. Each of these parts is then again decomposed into subsystem, e.g. the engine consists of one engine block, four pistons, etc. Subsystems like the engine, door, wheel, etc. have structures to the right. These structures illustrate variants of the subsystems. For instance two types of doors exist – a front seat door and a back seat door.

In general, the structure to the left describes the structure of the product and all the subsystems (part-of structure). Whereas, the structures to the right describe all the variants of the subsystems or components (kind-of structure).

Class definition

The concept of classes in a PFMP is identical to the one used in the object-oriented paradigm, i.e. a group of objects sharing a common structure and/or behaviour. This implies that a class encapsulates a description of one or several elements. Examples are “A low profile tire” or “Tires”. A class can be one or several parts, e.g. a tire. Also, a class can be a group of descriptive attributes, i.e. colours, prices, etc.

Each class is given a unique *name* as identification. The name has to be unique in order to avoid misunderstanding. A class is represented in the PFMP by a horizontal line with a circle at the right end (—●). The class name is written next to the circle. The font applied is normally black (Figure 61).

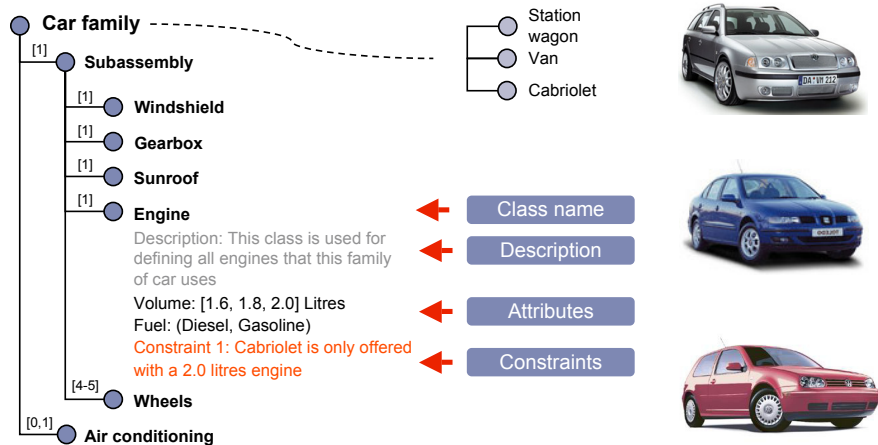


Figure 61. Principle class declaration in a PFMP. The small example shows a PFMP for a car family.

The name of a class should be relatively short. In cases, where more information about the contents and the purpose of the class is needed, a *description* field can be applied. The description field is used for a verbal description. In cases where the class is given the name of a part number, the description field is useful. The description is written below the class name in the PFMP with a grey font (Figure 61).

Classes can include *attributes*. The attributes define the variation within the class e.g. Colour (Blue, Green, Red, Yellow). The attributes are listed below the description field of the class, or in case of no description field, the attributes are listed just below the class name. Further description of an attribute declaration is found on page 113.

Constraints prescribe how classes and attributes can be combined. Constraints, which are written in text, are listed below the list of attributes. A red font is normally applied for declaration of constraints.

Class hierarchy, i.e. part-of and kind-of structures

Classes are used for creating the hierarchy in the part-of structures and the kind-of structures. A class can consist of one or more classes. A class below another class is so-called a *sub-part*. The sub-part (class) is a part of the declaration of the super-parts. A *super-part* is the class above another class. Super- and sub-parts are illustrated in Figure 62.

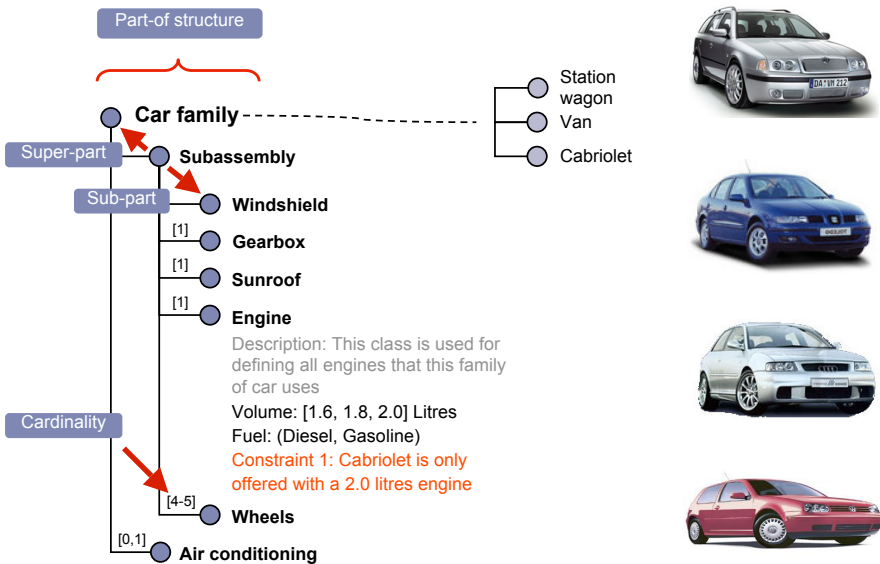


Figure 62. Sub-/super-parts relative for a particular class. In this example the class “Car family” is the super-part for the class “Subassembly”. The class “Wind shield” is the sub-part for the class “Subassembly”.

A class in the part-of structure (not kind-of structure) is given so-called *cardinality* (Figure 62). The cardinality describes how many of a particular sub-part that a super-part consists of. A car has four wheels. This implies that the cardinality of the class wheel is [4]. The cardinality is expressed as a number (e.g. “[2]”), interval (e.g. “[2-7]”) or a fixed set of numbers (e.g. “[2,5,6]”).

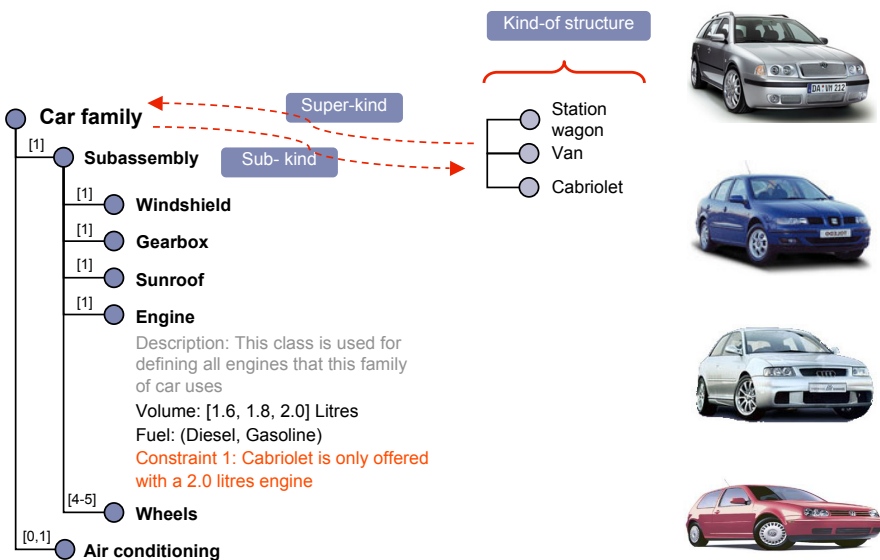


Figure 63. Super-/sub-kinds are relative for a particular class. In this example the class “Car family” is the super-kind for the class “Station wagon”. The class “Station wagon” is the sub-kind for the class “Car family”.

The kind-of structures are used for displaying the variety of a given class. Equivalent to sub-/super-parts, *sub-/super-kinds* represent the specialisation and the generalisation respectively of a given class. The concepts of sub-/super-parts and sub-/super-kinds are relative to the particular class, Figure 63.

Attribute definition

Attributes are the descriptive parameters of a class, i.e. colour, weight, price, part number, etc. It corresponds to a variable in traditional programming. The attributes describe the variation of a class, e.g. Colour (Blue, Green, Red and Yellow).

The PFMP utilises four types of attributes: identifier, real, integer and Boolean. These types of attributes are described in the following:

- *Identifier* – An attribute of the type identifier is expressed by a text string, e.g. Colour (Red, Green, Blue)
- *Integer* – An integer is a whole number, i.e. a number that does not have a fractional part. It can be positive, negative or zero, e.g. ..., -3, -2, -1, 0, 1, 2, 3, ... Integers can be expressed as numbers e.g. "[2]", interval e.g. "[2-7]" or a fixed set of numbers e.g. "[2,5,6]"
- *Real* – An attribute of the type real is any rational or irrational number. Real numbers can be expressed as a number, e.g. "[2.7]", interval e.g. "[2.7 .. 5.7]" or a fixed set of numbers e.g. "[2.7, 5.6, 6.9]"
- *Boolean* – A attribute that has the nature of being "True" or "False" is denoted a Boolean, e.g. Hard drive (True, False)

The attributes are declared as a part of a class declaration. This implies that the attributes are listed below the class in the PFMP (Figure 61). The formal way of declaring an attribute is by stating the attribute name. Hereafter, the domain of the attribute is listed. In case of attributes that have a unit, this is listed afterwards. An example of a declaration is "Weight [20 ... 77] [kg]".

Constraint definition

A PFMP might include many components and modules, which can be combined into final products. However, typically there are limitations for how the components and modules can be combined. To express such limitation, the concept of constraints is introduced. A constraint is a rule that expresses how classes and attributes can or cannot be combined. Four types of constraint expressions exist:

- *Verbal* – The constraint is expressed in one or more sentences, e.g. "An open sports car cannot have a sunroof"
- *Logic* – Logic constraints, e.g. "Sports_car -> NOT sunroof". Logic is powerful for expressing complex configuration problems with only few constraints.
- *Calculation* – Constraints of the type calculations represent math equations, e.g. "Car_weight = Engine_weight + chassis_weight"
- *Combination table* – Tables can also be used to express constraints. Such a table states how components can be combined (Table 7).

		Parts																									
		Pistons												Gaskets								Rods					
Subassemblies	F22-HG123	1												1		1				1							
	F22-HG124		1												1		1		1		1						
	F22-HG125			1												2					1						
	F22-HG126																					1					
	F22-HG127			1												3						1					
	F22-HG128																2						1				
	F22-HG129				1	1										2											
	F22-HG130																										
	F22-HG131																										
	F22-HG132															2		2									
	F22-HG133																		2						1		
	F22-HG134																									1	
	F22-HG135																									1	
	F22-HG136																								1		
	F22-HG137																								1		

Table 7. The example in the above constraint table illustrates how the components (Top row) can be combined into subassemblies (Left column). The highlighted example shows that assembly “F22-HG130” consist of 1 “P3_H218 piston”, 2 “G3_H212 gaskets” and 1 “R3_H214 rod”.

A constraint is always declared in a class, even though the constraint refers to several classes. It would not be semantically correct, if the same constraint is declared in several classes and it would make the maintenance of the PFMP difficult.

A constraint is given a number or a name as unique identification. The constraint is declared in a class and is written with a red font (Figure 61). In case of application of tables these are inserted in the PFMP. The name/number of the constraint is posted above the table and also within the class declaration.

Concluding on the PFMP formalism

The formalism described in the above is generic and does not in itself describe how to model a product or product family. To do so the proposed formalism is combined with the artefact theories: Theory of technical systems and the Theory of domains. In this research it is done by introducing three views in the PFMP, i.e. customer, engineering and part view.

15.3 Modelling formalism for customer view

The objective of introducing a customer view in a PFMP is to describe the product families from a customer’s point of view. This means to model the commercial variety of a product family. Product families typically include variety that does not have the customers’ interest, e.g. variety of screws. Such variety is not included in a customer view.

The primary interests of the customers are likely to be the behaviour of the product, but the customer might also have preferences concerning the structural aspects, e.g. the type of rims of a car. Consequently, a customer view in a PFMP can include structural or behavioural descriptions of the product family.

The modelling formalisms applied for a customer view are:

- *Technical process modelling* – Technical process modelling is based on the technical process system described by the Theory of technical systems, HUBKA 1973 (Page 30).
- *Interface modelling* – The interfaces among the product and the system, which it is connected to, is also an approach for structuring a customer view.

- *Feature modelling* – Feature modelling deals with modelling of features that customers select among, as the customers specify a product.

Process modelling in a customer view

The variety of a product family should reflect the different types of applications that customers have. One way of modelling applications is to apply the technical process system proposed in the Theory of technical systems, HUBKA 1973.

A technical process system (Page 30) consists of four subsystems, a technical system (the product), a human system (the human operator), the environmental system (influence from the environment) and finally a technical process system (the meeting). Variation in the human system, the environmental system or the technical process system might imply variation in the product. Therefore all four classes of systems should be modelled.

When modelling technical process systems, such might have to be decomposed into subsystems as illustrated in Figure 64.

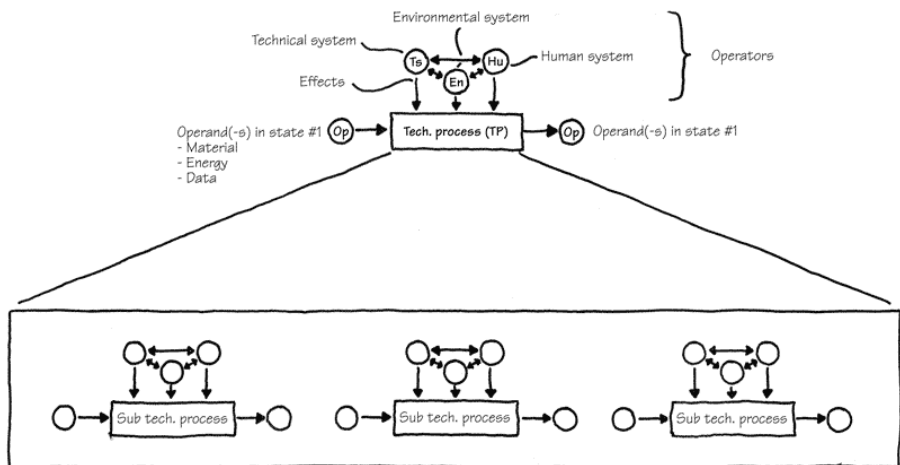


Figure 64. A technical process system (Page 30) consists of four subsystems, a technical system (the product), a human system (the human operator), the environmental system (influence from the environment) and finally a technical process system (the meeting). A technical process system can be decomposed into sub process systems.

Two approaches can be applied for modelling a process system; a formal and an informal formalism. The formal formalism includes all four subsystems: a technical system, a human system, the environmental system and finally a technical process system. The informal approach only includes the subsystems what generate variety within the product family.

Formal technical process modelling – One class is used for defining the technical process (a meeting) and it has four underlying classes. These four classes represent the technical system, the environmental system, the human system and the operands, AUGSBURG 2000. This is illustrated in Figure 65.

Informal technical process modelling – Another approach for modelling processes in a customer view is to only include the aspects of the process system that are of interest or that generate variety.

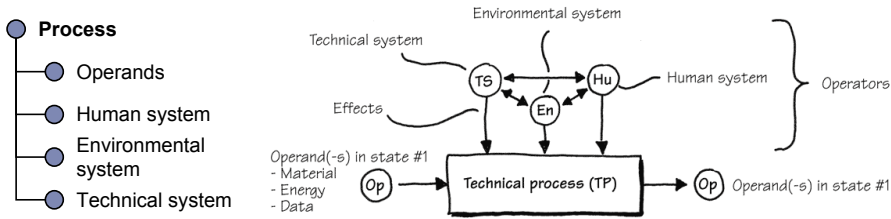


Figure 65. Left: Formalism for modelling a technical process system in a customer view. Each subsystem is represented in a separate class in a part-of structure.

Interface modelling in a customer view

Another way of describing how customers see the variety of a product family is by modelling the interfaces of the customers’ applications and how they vary. The customers’ applications, which the product family is a part of, often demand certain features in the product. One way of presenting this in a customer view is by modelling the variety of interfaces in the customers’ applications. Examples of such interfaces for a pump family are the electrical input (power frequency and voltage), size of flanges, type of flanges, etc.

Interfaces are represented in a PFMP by means of classes. Variety among the interfaces is presented in kind-of structures (Figure 66).

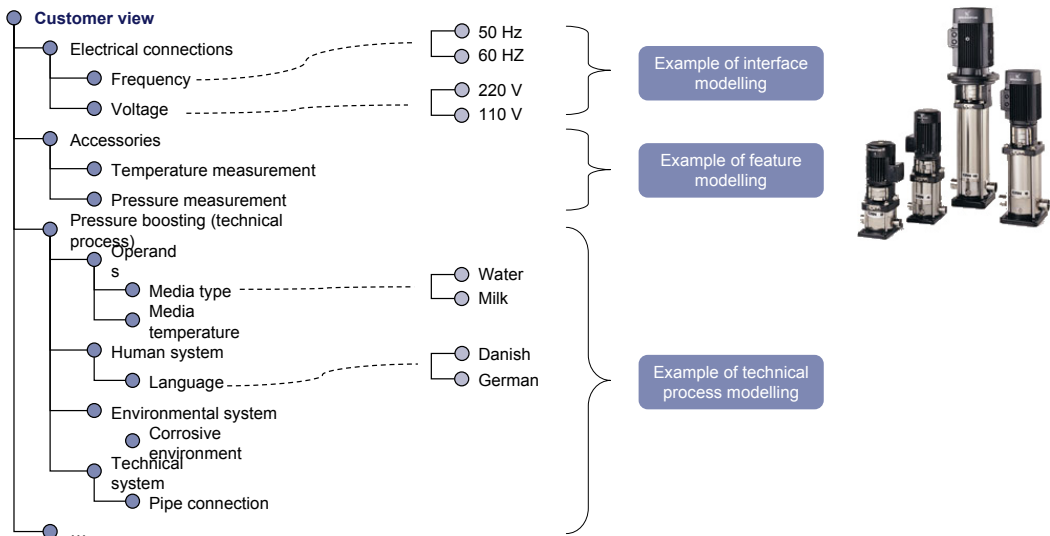


Figure 66. An extract from a customer view for a pump family. The model shows examples of interface, feature and technical process modelling.

Feature modelling in a customer view

A third way of structuring a customer view is by modelling the variety of features that are offered to the market. Examples of such features for a car family are colours, type of rims, sunroof, navigation system, etc.

Features are represented in a PFMP by means of classes. Variety among the features is presented in kind-of structures (Figure 66).

An example of a customer view

Figure 66 includes an example of a customer view for a pump family. The customer view includes examples of how interfaces, features and processes are modelled. The three different types of modelling can be mixed if needed.

15.4 Modelling formalism for engineering view

The purpose of modelling the assortment from an engineering view is to describe how the assortment is functioning and to show the functional variety. Contents of the engineering view are the elements in an assortment, which realise functions i.e. organs and organisms. The starting point for identification of the engineering view will often be identification of the main functions within the assortment. After this, the main carriers, i.e. organs and organisms, are determined. This will be followed by identifications of sub-functions and related organs until all major functions of the assortment are described. If only one class of organs exists they will be placed in the part-of structure, otherwise as alternatives in the kind-of structure.

Modelling in the engineering view is relevant because it is difficult to get an overview of a complex assortment by modelling physical parts. Furthermore, functionality is often one of the main starting points for identification of standard designs.

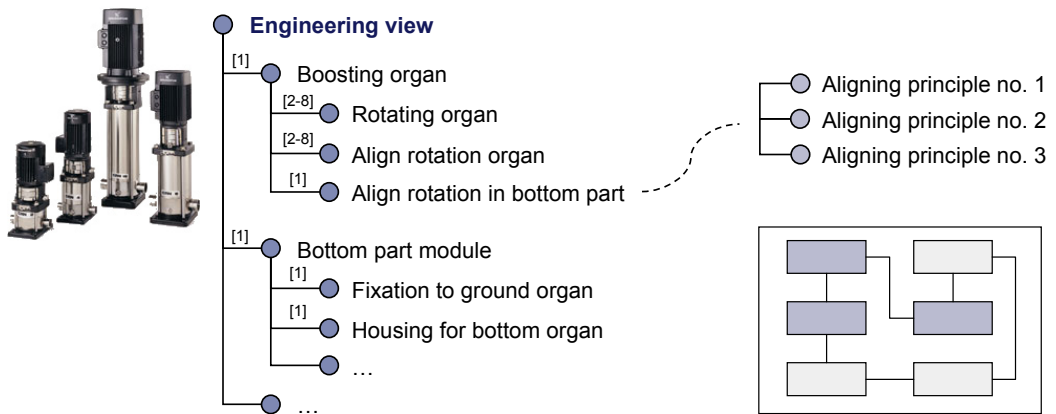


Figure 67. An extract from an engineering view for a pump family.

Organ modelling in an engineering view

As an engineering view is based on an organ model, the classes in the engineering view represent the organs. The engineering view presents the structure that can also be modelled by means of generic organ diagrams, as it is illustrated in "Tool: Generic organ diagram" (Page 100).

The engineering view of a product family is presented by means of classes in the part-of structure. Each class represents an organ or a group of organs. Variety among the organs; these are represented by means of kind-of structures (Figure 67).

An example of an engineering view

Figure 67 includes an example of an engineering view for a pump family. The model includes examples of organs, sub-organs and variety of the organs.

15.5 Modelling formalism for part view

The purpose of the part view is to describe the physical structure of a product family. Contents of the part view are assemblies and parts. This view is in principle all the bill of Materials within a company shown on top of each other. In the part view the generic part-of-structure often contains different superimposed structures, such as assembly sequence, sub suppliers, competences (e.g. mechanical, electrical, software engineering).

Modelling in the part view is relevant, because it describes the variety that has to be handled in all the functional areas of a company. Each of the variants has to be purchased, documented, planned during production, storage handled, etc.

An example of a part view

Figure 68 includes an example of a part view for a pump family. The model includes examples of assemblies and variation of the components within the assemblies. The modelling formalism applied in the part view follows the general description described earlier.

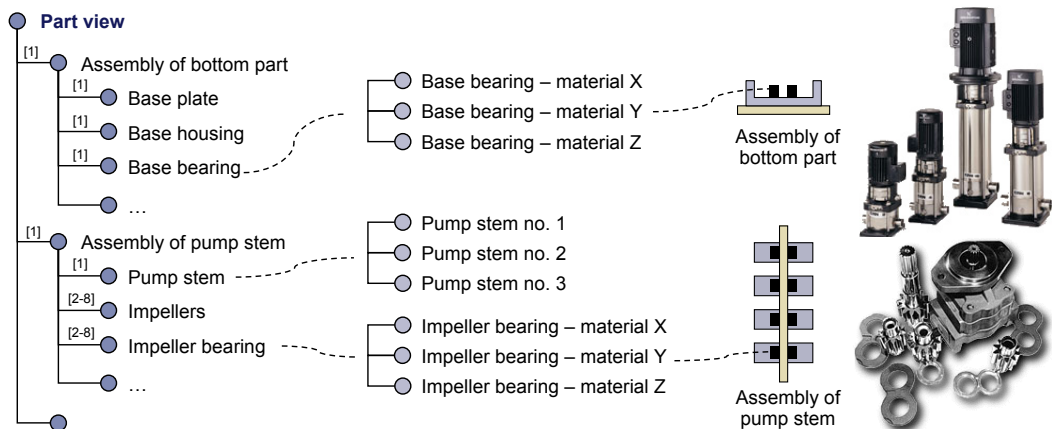


Figure 68. An extract from a part view for a pump family.

15.6 Coherence among a customer, an engineering and a part view

The three views are causally linked, ANDREASEN 1980 and HUBKA 1973. There exist causal links between the customer, engineering and part views (Figure 69). Features in the customer view are realised by one or more organs in the engineering view. The organs in the engineering view are realised by one or more parts and assemblies in the parts.

Parts/assemblies contribute to realisation of organs and organs contribute to realisation of features in the customer view. These causal links are important for making decisions on product assortments and architectures. The next section will explain this further and provide examples.

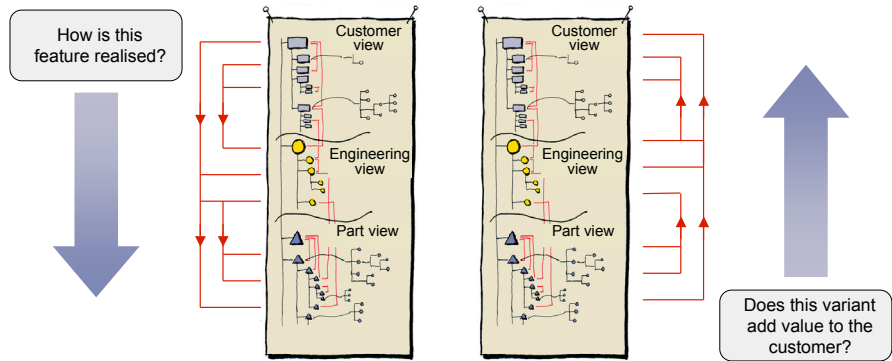


Figure 69. Coherence among a customer, an engineering and a part view.

15.7 Application of the PFMP

In different industrial projects (Table 2) the PFMP has been applied for making decisions concerning the assortment and architectures. Below four examples are explained:

Identification of value and non-value-adding elements – Due to the causal links between the three views, it is possible to identify the reasons for existence of product elements, e.g. a part/assembly. An example is a conveyer belt family. The conveyer belt family has three different chassis elements (parts in the part view), which enable three different mounting systems (organs in the engineering view). These three mounting systems reflect different application situations (features in the customer view). A closer study of the assortment and customers shows that only one mounting system is necessary, thus two variants are non-value-adding. Experiences show that often variety exists in a product assortment, which is non-value-adding and should therefore be removed from the assortment. In practise it is often difficult to remove non-value-adding variety due to e.g. spare part obligations for the existing product assortment or the installed base.

Identification of engineering complexity – The causal links between customer and engineering view provide an indication of the complexity, when developing customer specific variants. If e.g. a certain feature in the customer view has links to several organs in the engineering view, it indicates that when customers want a new variant, several subsystems have to be re-designed. In a new architecture and platform the product might be designed in such a way that fewer subsystems have to be changed.

Creating consensus between sales, engineering and production – One can argue that a certain aspect of a PFMP already exists in companies. Sales has their documents and IT systems describing what is relevant for Sales; Engineering has CAD and PDM systems describing the engineering aspects and Production has ERP systems describing what is relevant for realisation. In order to determine the “goodness” of the assortment, the links between the three views have to be described. This very seldom exists in companies. The PFMP forms a professional tool for a dialogue between Sales, Engineering and Production. It forms a basis for scoping of platform and architecture projects.

Documentation of the platform and architecture – If the company has a certain size and e.g. development at several locations, it is necessary to document the architecture. This is relevant both during development and final documentation. Some companies have utilised

the PFMP for documentation of decisions during development. In architecture projects it is often unclear what elements that have been decided and what are still being discussed. During development of a new architecture some companies have introduced a kind of “standard design manager role”, which updates the PFMP as the project proceeds. Elements that are decided are marked green and elements that are being considered are marked yellow.

15.8 Industrial application: Describing the variety of a product family

One of the companies that has adapted the PFMP as a tool for describing the variety of their product families, is Alfa Laval Kolding A/S (Denmark) and Alfa Laval Lund AB (Sweden). The following includes an example of one of PFMPs from Alfa Laval. The objective of introducing this particular case in this research is to illustrate how the three views have been applied at Alfa Laval and to illustrate how the three views are linked together.

The product family - ThinkTop

The product family described in the following is called “ThinkTop”. A ThinkTop is a mechatronic device, which controls a valve used in the food and pharmaceutical industries. Figure 70 includes a picture of a ThinkTop (the blue device) that is mounted on top of a valve. A ThinkTop measures the position of stem of the valve, i.e. how open or closed is the valve. A ThinkTop can adjust the position of the valve stem by means of air pressure.

The objective for this small project at Alfa Laval was to test the PFMP as a tool for getting an overview of the structures of product families. Successful application of the PFMP would be followed by introduction of PFMP as a global tool at Alfa Laval. It is chosen to introduce the PFMP of ThinkTop in this research, because it is a relatively simple product family – a low complexity and a low number of variants (about 500 variants).



Figure 70. Left: Picture of ThinkTop (blue device) mounted on top of two valves.
Right: Photo of two people standing in front of a print-out of a PFMP for ThinkTop. The size of the PFMP is about 80 x 110 cm.

Customer view - Interface modelling

The approach applied for the customer view was to model the aspects, which specify the specific product variant that a customer needs. In this case these aspects relate to the type

of valve that the ThinkTop is mounted upon and the different interfaces that it connects to. The interface modelling approach (Page 117) has been applied for the customer view for ThinkTop (Figure 71).

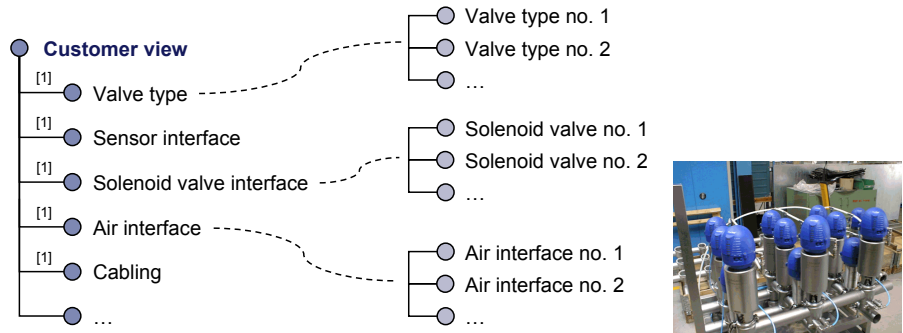


Figure 71. The principle structure of customer view for ThinkTop. The interface modelling approach (Page 117) has been applied in this case.

Figure 71 illustrates an extract of the customer view. The part-of structure in the customer view includes: Valve type, Sensor interface, Solenoid valve interface, Air interface, Cabling, etc. Variations of the interfaces are represented by means of kind-of structures. Due to confidentiality the classes in the kind-of structures have been made anonymous.

Engineering view - Modular structure

The engineering view for the ThinkTop family reflects the modular structure of the product. This implies that the classes in the part-of structure represent modules, e.g. Adapter module, Base module, Sensor system, etc. (Figure 72).

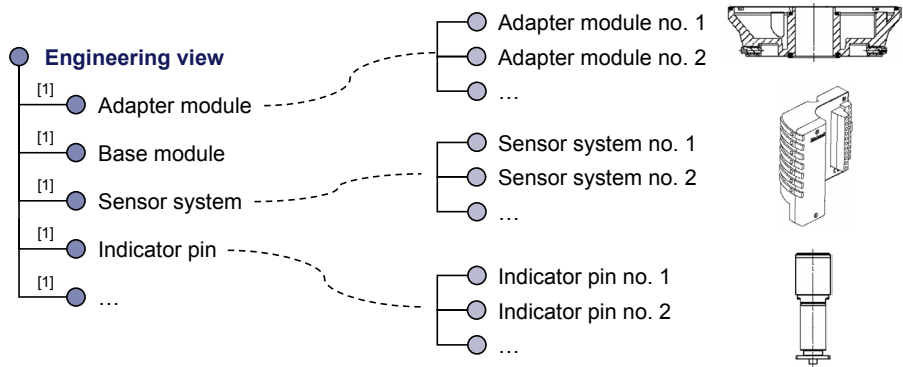


Figure 72. The principle structure of the engineering view of ThinkTop. The structure represents the modules within the product family.

The kind-of structures in the engineering view represent the variants of the modules (Figure 72).

Part view - Generic part structure

The part-of structure in the part view of the ThinkTop is identical to the structure of the engineering view due to the modular structure of the product. However, the part view is

detailed further to include all components. The approach has been to create a generic part-of structure. This implies that the part-of structure only includes components, which are included in all product variants (Figure 73). Consequently, the kind-of structure includes part-of structures. These part-of structures in the kind-of structures include the components that vary.

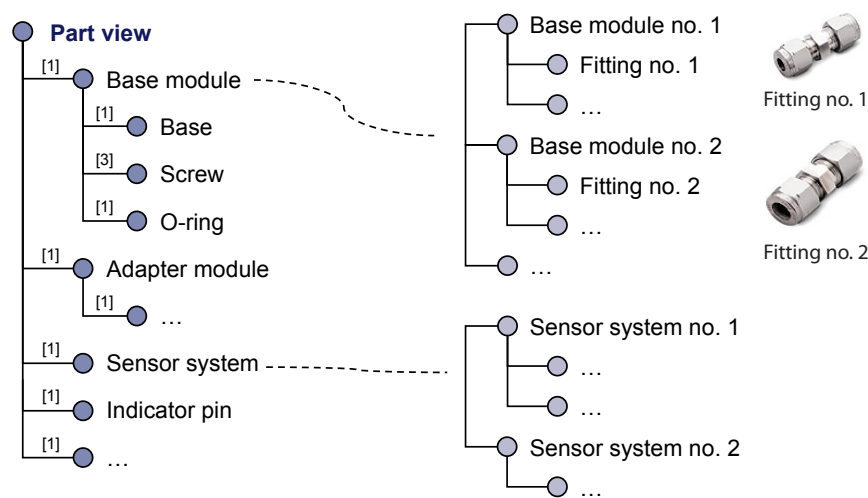


Figure 73. The principle structure of the part view for ThinkTop.

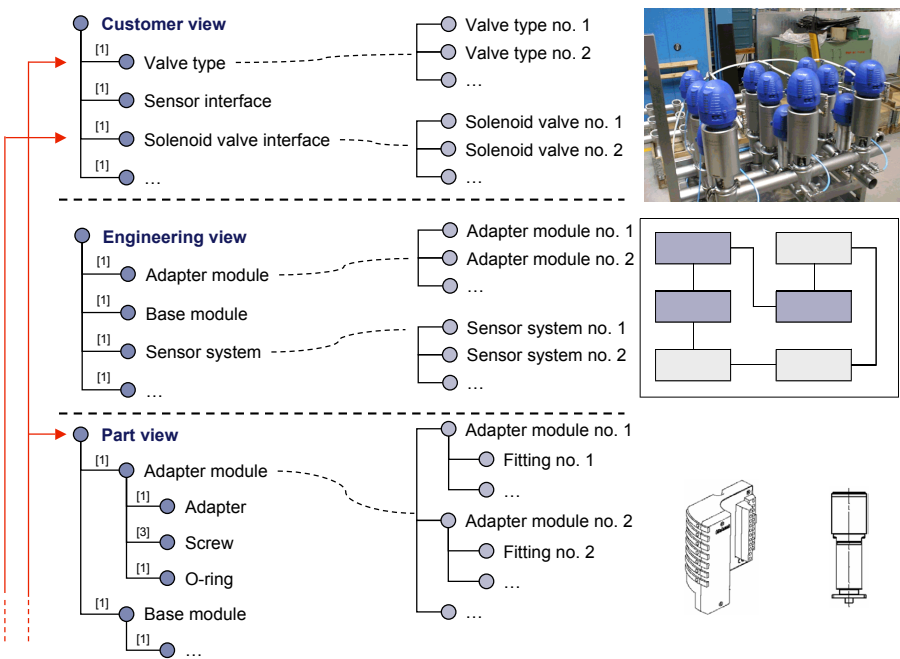


Figure 74. Extract of the PFMP for the ThinkTop. The model shows how the customer, engineering and part views are linked together by means of red lines.

Coherence between the views

The three views in the PFMP for the ThinkTop are linked together and hereby reflect the coherence between the three views. Figure 74 illustrates how the views are linked together. The red lines to the left show some of the relations.

The links between the views are used for two purposes:

Changes in the customer view – If changes occur in the customers' applications and therefore in the customer view, the red lines illustrate, where in the product family modifications might have to be done. One example could be that Alfa Laval introduces a new type of valve to the customers. This would imply that the class "Valve type" is changed. Following the red line from this class and downwards, it appears that this class influences the classes: Adapter module, Indication pin, etc. This is caused by the fact that the Adapter module and the Indicator pin are physically connected to the valve. Introduction of a new valve might therefore cause changes in the ThinkTop. Another example could be that new interfaces occur in the customers' applications. This could affect the design of the ThinkTop family. Such changes are all illustrated by means of the red lines.

Changes in the product family – Alfa Laval are continually improving their products and process to meet the needs of the customers and stakeholders. Such changes might involve modification in some of the components. The red line in the PFMP can be used for illustrating how changes in one component might affect the customers' needs.

Conclusion

The case above shows that it is possible and meaningful to describe a product family by means of a PFMP that includes a customer, an engineering and a part view.

Feedback from Alfa Laval:

- *"We have each component documented by means of drawings, purchase specifications, etc. however, this is the first time we have an overview of the entire product family."*
- *"If I left Alfa Laval, my follower would have a hard time understanding the reasons for the variety. But with a PFMP, my follower would have a much easier start"*

The tool was successfully applied and PFMP afterwards has been introduced as a tool for modelling product families at Alfa Laval globally.

15.9 Industrial application: Re-structuring bill of materials (BOMs)

In recent years many companies experience an increase in the variety of products. Many reasons exist for this increase of variety. One of the key drivers is the need to fulfil the variety of customer needs. As the number of different products increase it is likely that the variety of bill of materials (BOMs) also increase.

BOMs are typically managed in Enterprise Resource Planning systems (ERP-systems). Such systems are sophisticated databases. BOMs are normally handled within the computer, but ERP-systems have functionalities that enable printing of individual BOMs. But printing all BOMs can be very difficult. One ERP-expert expressed it this way *"I tried printing all BOMs for one of our product families, but after printing 10.000 pages I had to turn of the printer to prevent a break down."*

The objective of this case is to illustrate that PFMP can be applied for visualisation of BOMs. In this case one PFMP should include all BOMs, parts, assemblies, services and operations of a product family. The PFMP should form basis for a re-structuring of the BOMs. This means to simplify the BOM structures and to reduce the variety of BOMs, without changing the product assortment offered to the markets. Finally, the benefits from re-structuring the BOMs should be quantified by measuring the reduction of BOMs and BOM-items (i.e. parts, assemblies, services and operations).

Current situation

This case is based on a project carried out at YORK Refrigeration, Denmark. YORK is a manufacturer of compressors typically used in cold storage warehouses, rinks, production sites, etc.

Figure 75 includes two examples of YORK product families. Each product family consists of about 16,000 different BOM-items. The products are tailored to the customer by means of a sales configuration system. Some YORK product families are more than 25 years old and a lot of variants have been added over time to meet the customers' needs. This has led to an increasing number of BOMs.

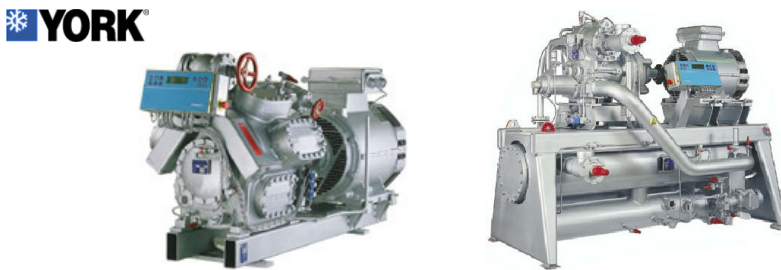


Figure 75. Left: An example of a YORK reciprocating compressors (SMC 100). Right: An example of a YORK screw compressor (SAB 163).

The current BOMs are affected by all the product variants generated from sale of customer specific products. The ERP-system, which stores and manages the BOMs, has changed twice and this has affected the BOMs as well. Each ERP-system has its way of handling BOMs and structuring the BOMs. Currently, YORK is changing to a third ERP-system. YORK has the choice of copying the old BOMs or re-structuring them. YORK has chosen to re-structure the BOMs in order to simplify the structure and the volume of BOMs. The objective was to ease the implementation in the new ERP-system and to ease maintenance of the BOMs in the future.

Automation of PFMP

The amount of data in an ERP-system is overwhelming and to make PFMP for such product families can be time-consuming. Consequently, a software programme was designed to create a PFMP based on the data in the ERP-system. The BOM-data in the ERP-system was structured by means of relations similar to part-of and kind-of relations ("The basic PFMP modelling formalism", Page 110). Because the relations exist in the ERP-system, it was possible to create a software programme that builds one PFMP including all BOMs and BOM-items for one product family. The programme enabled creation of PFMP within a few min-

utes. A process that otherwise would have taken weeks.

The outcome was a PFMP, i.e. one piece of paper including all BOMs of one product family (Figure 76.). In the case of SAB 163 screw compressor family (Figure 75) the PFMP included 16,000 items, i.e. parts, services and operations. The piece of paper had the size of 3 x A0 posters (0.8 x 3.5 m). Hereby, all variants and all items were posted and structured on one piece of paper as illustrated in Figure 76.

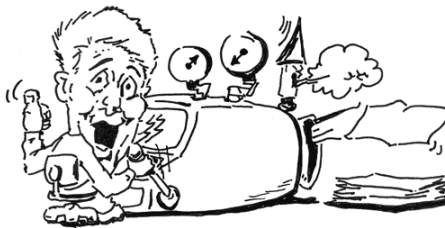


Figure 76. A PFMP was created based on the ERP-date by means of a software programme. The outcome was the PFMP shown on the picture. The PFMP showed all BOMs and BOM-items for the product family SAB 163.

PFMP structures

The PFMP applied at YORK consisted of two views – a customer view and a part view. The reason for the customer view was to identify all the parameters that define a unique product from a customer point of view. Based upon these defining parameters it was possible to identify one specific BOM. The part view was needed because it was the view including the BOMs. The part view was automatically created as described before. But the customer view was created manually.

The customer view described all the parameters that define a product from a customer point of view. Examples of such parameters are power frequency, type of liquid, temperature, etc. The customer view was created based upon all the defining parameters, which existed in the configuration system. The SAB 163 screw compressor family had 152 classes of defining parameters with a total of 702 defining parameters. An example of defining parameter is "power frequency" and its defining parameters are "50 Hz" and "60 Hz".

The part view described all BOMs including parts, assemblies, services and operations. The part view was auto-generated as described in the above. This implies that the structure was identical to the structure of the existing ERP-database (Figure 76).

Re-structuring process

The process of re-structuring the customer and part views to smaller and simpler views was a manual process. This process was driven by domain experts, i.e. staff with detailed knowledge of the product family, the applications of the products and the production system.

The customer view was re-structured and simplified by classifying the defining parameters. The top level classification was shown in Figure 77. The parameters were classified into those that relate to the customers "application" (e.g. liquid) and to the "product" (e.g. motor

brand). The parameters related to the product itself were again decomposed in the different subsystems (Figure 77).

After classification of the defining parameters, each parameter is evaluated. Duplicates and unnecessary parameters were removed. The classes of defining parameters (e.g. power frequency) in the customer view were reduced from 152 to 35 parameters. The defining parameters (e.g. 50 Hz) were reduced from 702 to 130 parameters. The reason that such a reduction was possible is that BOMs had evolved over time and new BOMs were added based on old inappropriate structures. The reduction was possible because the old existing ERP-system had limitations in the way of declaring the defining parameters.

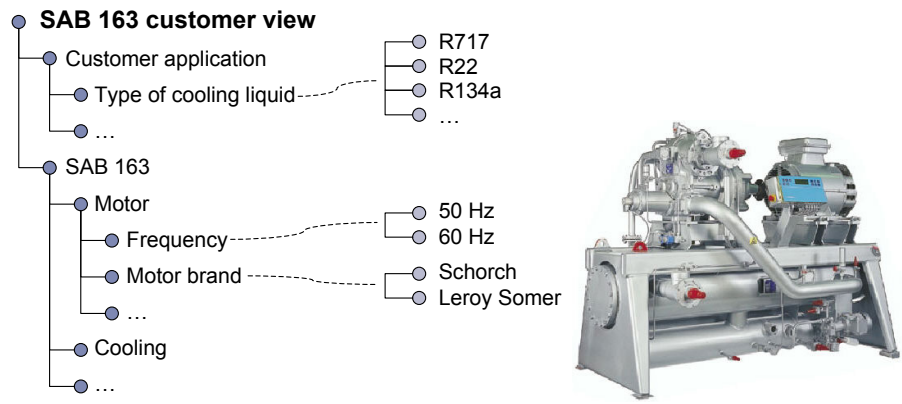


Figure 77. Section of the re-structuring and simplified customer view.

After visualisation and printing the PFMP, the process of identifying simpler and smarter BOMs started. This is a manual process, where new structures were designed. The re-structuring process was driven by domain experts, i.e. staff with detailed knowledge of the product family and the production system.

The overall structuring principle for the new BOMs was a functional structure (i.e. organ structure). This implies that the parts, assemblies, services and operations were grouped according to the organs of the product. Figure 77 shows a section of the PFMP after re-structuring.

The size of the BOMs was reduced by 75%. This means that 75% of BOMs and variants of parts, assemblies, services and operations were removed. This reduction was possible because of a reduction of the defining parameters and because duplicates in the structures were removed.

Configuration constraints

The customer view and the part view were linked together in order to express the configuration constraints. These constraints were expressed by means of tables that link the defining parameters in the customer view to the individual part numbers, services and operations in the part view.

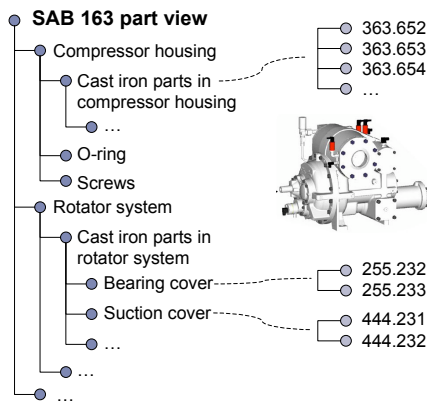


Figure 78. Left: Section of the re-structuring and simplified part view.
Right: Photo of the re-structuring process.

15.10 Benefits

The objective of applying PFMP at YORK was to visualise all the BOMs of their product families. The visualisation was done by means of the PFMP and by printing these on A0 paper. Hereafter, the BOMs were re-structured and simplified, without changing the product assortment offered to the markets.

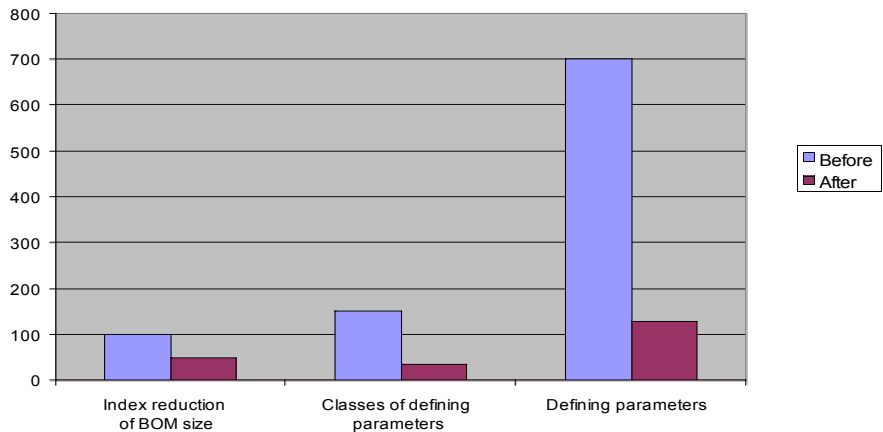


Figure 79. Statistics from re-structuring the BOMs for SAM 163 screw compressor family. Reduction of BOM-items (i.e. parts, assemblies, services and operations), classes of defining parameters and defining parameters.

The quantified benefits from the re-structuring of the BOMs were (Figure 79):

- The size of the BOMs was reduced by 75%. This means that 75% of BOMs and variants of parts, assemblies, services and operations were removed.
- The classes of defining parameters (e.g. power frequency) in the customer view were reduced from 152 to 35 parameters.

- The defining parameters (e.g. 50 Hz) in the customer view were reduced from 702 to 130 parameters.
- It was estimated that the number of configuration rules was reduced with about 50%. This was primarily due to the reduction of defining parameters in the configuration view.

The above quantified benefits are based on the SAB 163 screw compressor family. The other 19 product families, which have been through a similar restructuring, showed similar benefits.

Not all benefits were quantifiable, but other just as important benefits had been achieved:

- The migration from the old ERP-systems to the new one was relatively simple from a BOM structure point of view. This was due to a simpler and smaller BOM and defining parameters, which have been defined by means of a PFMP.
- The new BOM structures are structured according to organs in the product. This eases the navigation within the BOM structures.
- All product families have the same generic structure. It eases the process when staff move from working with one product family to another product family – the BOM structures are similar.

The experience from visualisation of BOMs shows that it was possible to visualise an entire product family on one piece of paper. This visualisation enables a professional dialogue about the BOMs and in this case it led to a reduction of the BOMs by 75%. Such a reduction eases the daily workload related to the BOMs. The benefits have been achieved without limiting the variety offered to market.

15.11 Conclusions on modelling variety

This chapter introduced a modelling formalism for modelling product families. The modelling formalism enables documentation of a product family's variety. The modelling formalism is constituted by three views (Figure 80):

- *Customer view* – The customer view describes the product family from the customers' point of view. This implies describing the variety offered to the markets.
- *Engineering view* – The engineering view describes the product from a functional point of view by means of organs. This implies describing the organs structure and the variety of organs.
- *Part view* – The part view describes the product family from a physical point of view. This implies describing the structure of the bill of materials and describing the variety of assemblies and parts.

The three proposed views in the PFMP are linked together and hereby describing the coherence among the views (Figure 80). The visualisation of the coherence among the views enables reasoning about the product family.

The two cases from Alfa Laval and YORK Refrigeration respectively show two industrial applications of PFMP. The Alfa Laval case shows how the three views in a PFMP can be applied for modelling the variety within a product family. The YORK Refrigeration case shows how

variety within a product family also is reflected in the BOMs and how a PFMP can be applied for modelling a product family based on bill of materials (part view) and a customer view.

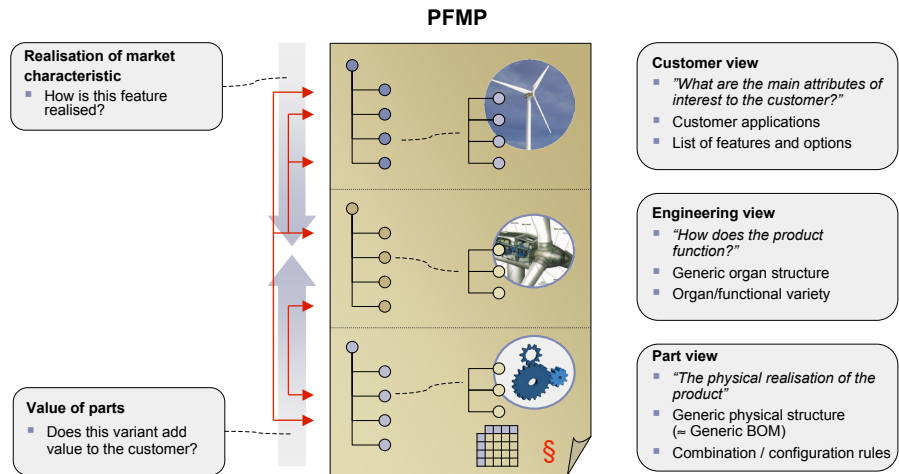


Figure 80. A PFMP includes a customer, an engineering and a part view. The views are linked together.

16 Conclusions on tools for developing architectures for product families

The objective of Part 4 was to introduce tools supporting development of architectures. The two tools proposed are denoted Generic organ diagram and Product family master plan (PFMP). The introduction to Part 4 (Page 99) argues that four aspects are central for modelling architectures:

- *Organs structures* – Both tools proposed in the above include formalisms for modelling the organs structures of product families. The generic organ diagram has the organ structure as its primary focus. The approach applied is inspired by traditional block diagrams. The PFMP has an engineering view, which has the organ structure as the core structure, for which the variety is described.
- *Organ interfaces* – The organ interfaces are a central part of describing the organ structure in the generic organ diagrams.
- *Visualisation of variety* – Both tools have ways of describing variety within the product family. The generic organ diagram enables modelling of variety among organs. The PFMP enables modelling of variety from three points of view. These are customer, engineering and part views. All three views are needed for meaningful reasoning on the "goodness" of the variety.
- *Linking variety* – The PFMP enables linking among the three views, which describes the coherence among the views.

The two tools proposed in Part 4 have in a number of industrial applications proven to be meaningful. However, the tools do not include all aspects related to modelling architectures. Some of the aspects, which are not full supported by the tools, are:

- *Classification of interface* – The formalism for modelling organ structures proposed in

Part 4 applies the interface definitions described in the literature. However, there is a need for studying the interface phenomenon further and for developing tools for documenting and managing interfaces.

- *Timing of standard designs* – A central aspect of standard designs and architectures is the timing aspect. The definitions emphasise that an architecture not only includes one product, but a product family or even several product families. The definitions also distinguish between existing and future products, standard designs and design units. A stream of new products has to be carefully planned in order to enable re-use. One way to ease “prediction” of the future is to plan by means of roadmaps. Roadmaps are widely used in industry. There is a need for investigation of how to model the timing aspects of standard designs and architectures and how to control this timing aspect.

Part 4 concludes that the proposed tools support development and documentation of product families based on architectures. It is also concluded that there is a need for development of new tools to reflect other aspects of architectures. Part 5 reflects on industrial applications of the tools proposed in Part 4.

Part 5

Industrial applications of architectures for product families

The thinking patterns, models and tools presented in this research have been applied in a number of industrial projects. Part 5 presents how these thinking patterns, models and tools have been applied at Bang & Olufsen and Vestas.

Part 5 shows examples of industrial applications on architectures that have been carried out within this research. During this research a number of projects have been carried out in cooperation with companies. Some of the projects have been carried out with focus on getting to understand the challenges that the companies face in relation to product families. Other projects have been carried out to verify the concepts of architecture and standard design (Part 3) and to verify the modelling aspects presented in Part 4.

The objective of Part 5 is to exemplify the application of the concepts of architecture and standard design and to illustrate how the modelling formalism has been applied. Part 5 should provide answers to:

- How has the tools and models been applied?
- What benefits are achieved from re-use of standard designs?

The industrial applications included in Part 5 have primarily been carried out at Bang & Olufsen. However, Part 5 also includes an example of application from Vestas.

Structure of Part 5 – Part 5 describes two industrial applications of architectures for product families. First, it is described how Bang & Olufsen has changed their development activities by means of architectures and standard designs. It is shown how they have become “better” at re-using. Hereafter, it is quantified how Bang & Olufsen save R&D resources through re-use of architectures and standard designs. The second case is from Vestas. It is shown how they are able to run development activities parallel by means of a family architecture.

17 Bang & Olufsen case: From reactive to proactive re-use

The reader may recognise Bang & Olufsen as a manufacturer of high-end audio and vision equipment for the consumer market. Their main positioning parameters are industrial design and high quality. Some may claim that re-use of standard designs is not in agreement with innovative products that are driven by industrial design. Nevertheless, Bang & Olufsen have implemented a re-use approach that enables them to re-use standard designs from one product to another. This has enabled Bang & Olufsen to cut down R&D resources and still be innovative.

This chapter shows how Bang & Olufsen have changed their development paradigm from reactive to proactive re-use. Bang & Olufsen comes from a situation where re-use took place when a project leader or a senior engineer “remembered” a solution from previous projects that could be re-used, i.e. reactive re-use. Today, Bang & Olufsen plans the re-use 3 to 5 years ahead, i.e. proactive re-use. This means that as they design a new subsystem, they plan and decide that the subsystem should become a standard design to be re-used in the future.

The objective of this chapter is to illustrate how Bang & Olufsen have changed their development processes. It is investigated to what extent the changes match the architecture and standard concepts described in Part 3.

17.1 The old way of re-using is too resource consuming

Re-use is not new to Bang & Olufsen. In the late 80's and the 90's they had a re-use approach, where larger parts of the electronics and software were re-used from one product to another (Figure 81). This approach was successfully implemented in the vision business, i.e. television. For several years Bang & Olufsen had two television platforms – one aimed at the high-end and one aimed at the medium television market. Many of the televisions that can be bought today in Bang & Olufsen stores are based upon one of these two platforms. These platforms do not follow the definitions within this research, as these are not based on an architecture.

The challenge for Bang & Olufsen with this re-use approach in the late 80's and the 90's was that it was very resource consuming to renew these platforms. At times, when a TV-platform was renewed, all engineering resources were drained from the vision department. Unfortunately, it was not an option only to renew a part of the platform at the time. Another disadvantage of this approach was that the platform was not flexible enough for new industrial designs. The new flat screen televisions were a challenge in particular because of the radical changes to the industrial design. However, this re-use approach was a success in the late 80's and 90's, but the conditions for television manufacturing have changed.

Today, Bang & Olufsen is changing their re-use approach to an approach that is inspired by Philips Consumer Electronics. This means to divide the platform into smaller platforms, i.e. standard designs. These standard designs enable Bang & Olufsen to renew the individual standard design without renewing all standard designs at the same time. This gives them a possibility for continually updating and introducing new technologies and features into the product portfolio. Another goal for the standard designs is that they should be more flexible than the old platforms. Hereby, it will be possible to a higher degree to adjust and optimise the standard designs to the individual needs of the product for performance and

industrial design.

Finally, the new re-use approach gives Bang & Olufsen an opportunity to be more *proactive* in the way of the re-use. It is possible by means of standard designs and architectures to develop these to meet the needs of products that will be developed 3 to 5 years ahead. This means that they are planning re-use 3 to 5 years ahead instead of deciding on re-use ad hoc as new products are to be developed, i.e. reactive re-use.

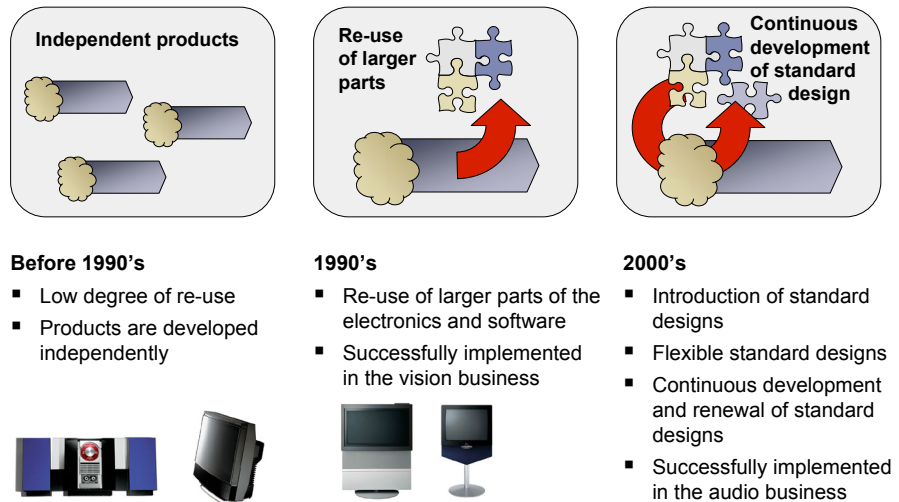


Figure 81. Bang & Olufsen implemented the first platform approach in the late 80's and the 90's, but they are now changing to a more flexible re-use approach.

17.2 The change process

The change from reactive to proactive re-use is not carried out over night. It is a change process that has taken at least five years and the R&D organisation has been re-structured three times. The following illustrates some of the changes that have taken place. The changes are illustrated by means of projects (Figure 82).

One of the first changes took place as *BeoSound 1* (ghetto blaster) was developed. The development team was forced by the management to halve the time-to-market. The means for this was to divide the product into modules and develop the modules in parallel. This approach was such a success that all newer products of more recent date are developed based upon this approach.

This approach provided Bang & Olufsen with experiences on decomposition of a product into modules and management of interfaces. This led to the assumption that it would be possible to develop modules that can be re-used. This formed the inspiration for the investigation of standard designs later on.

A consequence of the *BeoSound 1* project was an investigation of the possibilities of re-using. This project took its starting point in the loudspeaker families (Figure 82, "Loudspeaker project"). The objective was to determine if it would have been possible to develop the existing loudspeaker families based on re-usable standard designs. The result was that it would have been possible from a technical and functional point of view. However, it would

be too expensive to make radical changes in the existing products at this late stage of the life cycle of the products. The loudspeaker case is further described in “An example of application: Loudspeaker families” (Page 102).

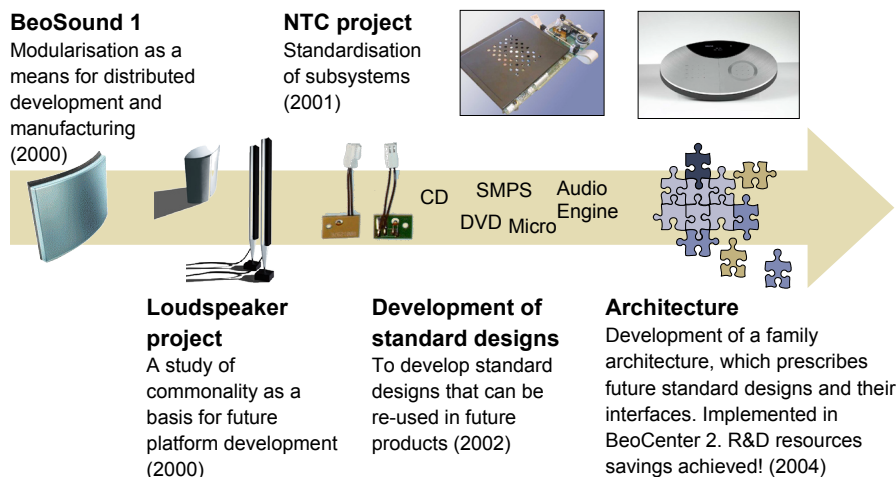


Figure 82. The process of changing from reactive to proactive re-use took at least five years. Here, the process is illustrated by means of projects.

Hereafter, several standardisation projects were carried out (Figure 82, “NTC project”). The objective of the standardisation projects was to verify that re-use is possible and beneficial. The project focused on small subsystems that were included in several product families. An example of such standardisation is the standardisation of the NTC printed circuit boards. The NTC is used for measuring the temperature of the amplifier of a sound system. The NTC must ensure that the product never gets so warm that the customer can get burned. These NTC are used in five different loudspeaker families and two television families, – but the technical solutions were different. A new NTC was developed and implemented in the seven product families. DKK 1.4 million was saved every year due to a cheaper solution.

The first business area to adapt the concepts of *standard designs* was the audio business area (Figure 82, “Development of standard designs”). Here a number of standard designs were developed and documented as prescribed in “Tool: Standard design document” (Page 145). Examples of such are CD, DVD, power supplies (SMPS) and audio engine. They were developed without a predefined family architecture. Formal application of standard designs would demand an assortment or family architecture. It was not until later that it was recognised that an architecture was needed for managing the standard designs. Nevertheless, the standard designs were developed and implemented in several products. As the standard designs were developed, it was studied and decided how the standard designs should be designed to fulfil the needs of the future products. Consequently, the standard designs follow the definition of a standard design (Page 78).

The latest change was the development of the *family architecture* for the audio portfolio. This architecture included the existing standard designs. This architecture is described in “The family architecture that BeoCenter 2 is based upon” (Page 139).

Along with different initiatives in terms of projects three organisational changes took place (Figure 83). These organisational changes reflected the emphasis of a higher degree of re-

use. The first organisational change was establishing of a *Re-engineering department*. The objective for this department was to focus on standardisation within existing products in order to reduce cost by means of e.g. standardisations.

The second organisational change was a re-organisation of a part of the R&D department according to technical disciplines, e.g. a CD group, a power supply group, etc. These groups initiated the development of the first standard designs.

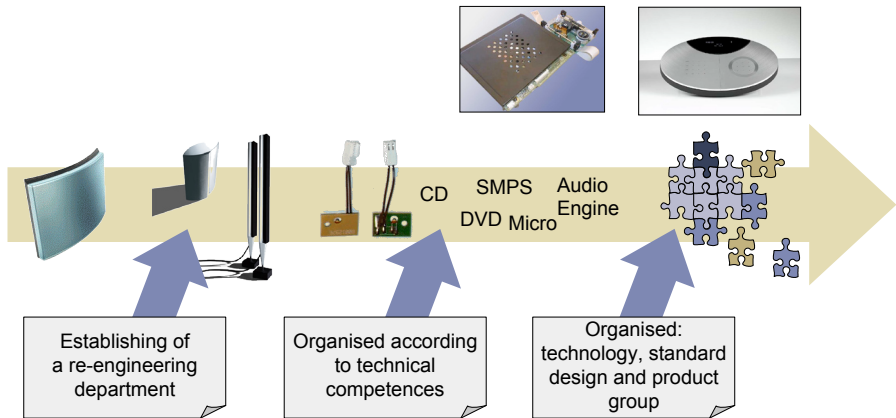


Figure 83. Three organisational changes occur in the period where standard designs and architectures are introduced.

By the third organisational change the R&D department was divided into a technology, a standard design and a project group. The technology group primarily had focus on new technologies and technologies that were not encapsulated in standard designs yet. The standard design organisation focused on the standard design, i.e. development, implementation and maintenance of the standard designs. Finally, the product organisation had the responsibility for developing the new products and using the standard designs.

The change process described in the above illustrates some of the steps that Bang & Olufsen has taken towards applying proactive re-use. It is a change process that reflects that the organisation adapts and refines the concepts architecture and standard design along with the change process.

17.3 The new design processes

As the conditions for re-use changed, the design processes also changed. Figure 84 illustrates three classes of development activities at Bang & Olufsen.

The *assortment and family architectures* are developed as independent activities (Top band in Figure 84). The goal for Bang & Olufsen is to have a television, an audio and a phone family architecture. Some of the standard designs are used in several family architectures, e.g. the DVD standard design is used in both audio and vision products. This implies coordination and coherence between the family architectures. Synergy between the family architectures is desired in such a way that products can communicate with each other (network) and hereby generate new functionalities for the customers. This is practiced by Bang & Olufsen by means of MasterLink (distributing of sound and images between products),

remote control features in the phones, traditional remote controls, etc. In the future it is expected that such functionalities will be further developed and controlled by an assortment architecture. Each family architecture is continually updated and renewed to ensure that they are up-to-date with new products, features and technologies.

The *standard designs* are developed in separate sets of activities (Middle band in Figure 84). Ideally, the standard designs should be fully developed before they are implemented in a product. Unfortunately, Bang & Olufsen does not have the resources in the standard design organisation to do so. Therefore, the product projects are used as leverage for developing and documenting the standard designs (Lower band in Figure 84). What takes place in the standard design development activities is a thorough design of the architecture of the standard design and specification of what to develop in the product project.

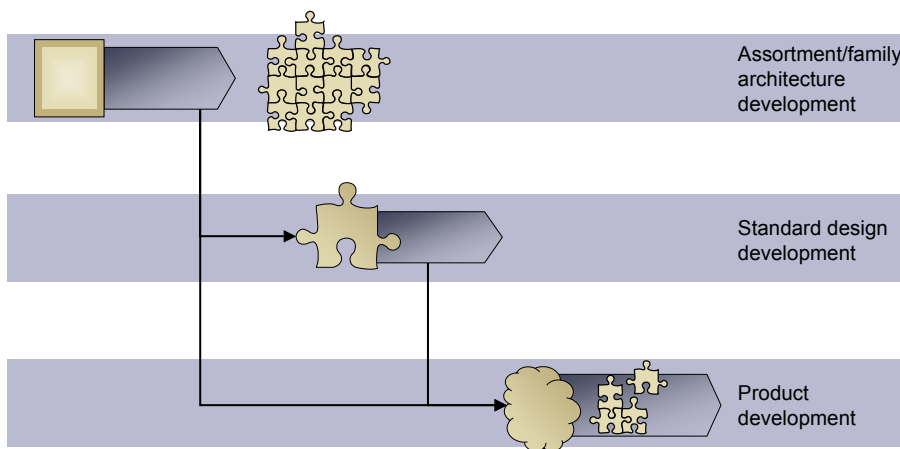


Figure 84. Three bands of development at Bang & Olufsen. The aim is to separate the design preparation (i.e. standard design and architecture development) from the development of the products.

In the *product development* activities the individual products are developed as Bang & Olufsen always has done (Lower band in Figure 84). What has changed is that product projects have a new kind of input – “ready-made” standard designs. Standard designs that are ready to be implemented. This gives the product projects a new level of readiness and a possibility to focus on what is new and unique for the concerned product and what is most important: time-to-market is reduced. The time-to-market is reduced as fewer R&D resources are needed for developing new products based on architectures and standard designs.

Another way of describing the new development processes at Bang & Olufsen is by describing the gradual creation of a standard design. The standard designs are “born” as the assortment or family architecture are developed (Upper band in Figure 85). It is here decisions are made on what should be or not be a standard design.

The standard design is an encapsulation of software, electronics and mechanics that fulfil a function (e.g. remote communication/infrared receiver). The choice of key electrical components, such as microprocessors and graphical processors, often influences the family architectures that Bang & Olufsen works with. It is therefore important to identify what key components to utilise, or at least limit the possible alternatives of key component to 2 or 3. The different key components supply different functionalities. Therefore, the choice of key

components also influences what functionalities that have to be developed by Bang & Olufsen. It is also at this stage that the key interfaces are identified, i.e. signals, power, protocols and space requirements. It is seldom possible to determine all details of the interfaces at this stage, but it is still important to identify the key interfaces because they may influence the design of the other standard designs. The standard design that is defined as the family architecture is developed and named *standard design concept* by Bang & Olufsen. This implies that not all aspects of the standard design are designed yet, - only the concept.

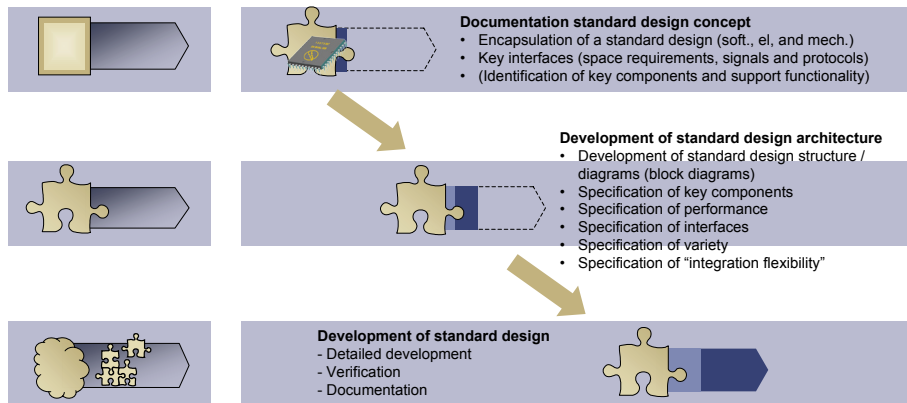


Figure 85. Gradual creation of standard designs within the three bands of development activities at Bang & Olufsen.

The standard design concept is input for standard design architecture development (Middle band in Figure 85). Here, the architecture of the standard design is developed. The architecture of the standard design is often represented by means of a standard design block diagram ("Tool: Generic organ diagram" Page 100).

As mentioned previously, it would be ideal if the standard design was fully developed and tested at this stage. However, this is seldom the case at Bang & Olufsen due to the size of the standard design organisation and due to the timing of new products. The solution is to focus on developing the architecture of the standard design and specify what to develop. It is the product projects that carry out the final development and documentation of the standard design. As the architecture of the standard design is developed, the following is specified:

- *Specification of key components* – From what supplier? What version?
- *Specification of variety* – What kinds of variants are needed? How is this variety to be implemented?
- *Specification of performance* – What performance and functionality should the standard design deliver? Should there be any variations according to the different needs of the different products?
- *Specification of interfaces* – Full specification of all interfaces, i.e. electrical, software and mechanics.
- *Specification of "integration flexibility"* – How flexible should the standard design be?

What kind of modification in the standard design is allowed from implementation to implementation?

It is when the individual products are designed that the standard design is developed, verified and documented in details (Lower band in Figure 85). These are new tasks for the product projects, because they will have to carry out more documentation and verification than previously. Developing a standard design in a product project may imply that the product project has to develop functionality that is not needed in the product concerned. However, the functionality might be specified from the standard design organisation in order to ensure that the specific standard design also is applicable for future products. An important issue for the product projects is that they are not left alone with the implementation and development of the standard designs. The standard design organisation supplies experts that help with implementation of existing standard designs and the development of new standard designs. The bottom-line is that the product project can deliver products faster to the market due to re-use of standard designs.

The above illustrates how Bang & Olufsen has adapted the concepts of architecture and standard designs in their new development processes. The new processes are not yet documented by means of new development models, but the processes take place due to an enthusiastic standard design organisation.

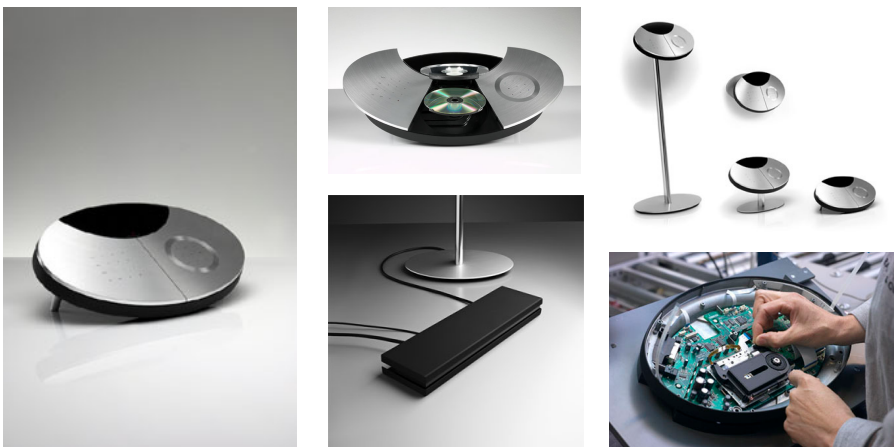


Figure 86. BeoCenter 2 – a music centre with CD, DVD, FM radio, AM radio, DAB radio, AUX and network functionality. BeoCenter 2 was based on a family architecture that other audio products will utilise in the near future.

17.4 The first family architectures at Bang & Olufsen

The first product launched based on family architecture was BeoCenter 2, which was launched in 2004. The family architecture of the BeoCenter 2 product complies with the definitions of architecture and standard designs. The following includes a description of the family architecture and a description of how the architecture was modelled. The modelling was based on the modelling formalism proposed in Part 4.

The product family BeoCenter 2

To understand the architecture and the importance of the architecture of BeoCenter 2 (Fig-

ure 86) one should know the basic functionality of the product. BeoCenter 2 is a music system that can play the audio and video sources: CD, DVD, FM radio, AM radio, DAB radio, AUX and MasterLink. MasterLink enables the BeoCenter to receive and distribute source signals to other Bang & Olufsen televisions or music systems. Also, MasterLink enables the user to control other Bang & Olufsen products through BeoCenter 2. In other words MasterLink is network functionality.

A radical new feature implemented in this product is the ability to play two sources at the same time, e.g. the BeoCenter 2 can play a DVD on a television and at the same time play radio on another set of loudspeakers in another room.

The features described in the above are the outcome of tradition in the audio business at Bang & Olufsen. This means that the features are “standard features”, which have been developed and refined over the years. However, the BeoCenter 2 also includes new features that future product also should benefit from. Consequently, a family architecture is developed for the BeoCenter 2.

The family architecture that BeoCenter 2 is based upon

As BeoCenter 2 was designed, other future product families were considered. These future products would include many of the existing features, e.g. FM tuner, MasterLink, DVD, etc.

It may come as no surprise that future audio and television products will be digital. However, the majority of today’s products are analogue, even though many of the sources are digital, e.g. CD, DVD, hard drives, etc. Changing from an analogue to a digital architecture is a radical change and such change is very resource demanding and the risk would be very high. To ease this change Bang & Olufsen chose to introduce the digitalisation in small steps. To do this it was chosen to develop a family architecture for the audio portfolio that over time could migrate from an analogue to a digital architecture. This should enable a high degree of re-use of the standard designs between the audio product families at low risk.

The following describes the family architecture of the BeoCenter 2 and how the architecture was modelled. According to previous definition a family architecture includes (Page 84):

- Existing standard designs
- Existing design units
- Future standard designs
- Future design units
- Interfaces among the units
- Interfaces with the surroundings

Figure 87 shows a schematic representation of the BeoCenter 2 family architecture, which includes standard designs and design units.

This family architecture includes the following design units (Figure 87):

Existing standard designs – FM tuner, CD drive, DVD drive, power supply (SMPS), Microprocessor and Audio engine were existing standard designs that the BeoCenter 2 was based upon. Each standard design complies with the rules: Decision of re-use, documentation and responsibility - as it is prescribed in “Standard design” (Page 79). Some of these stand-

ard designs existed in different version and variants. The variety was primarily caused by specification (Price vs. performance) and national standards. The BeoSound 2 was the first product to benefit from DVD, power supply and audio engine.

Future standard designs – The family architecture included standard designs that had not been developed yet. Examples of such were a digital radio tuner (DAB), a digital add on to the analogue audio engine and a new power supply (SMPS). These future standard designs were included in the family architecture, because they would influence the design of the existing standard designs. For example, if future products should re-use the analogue audio engine together with a new digital add on, the analogue audio engines should be prepared for this. This implies that the analogue audio engine should include features and interfaces that were only utilised as the new digital add on was used. Consequently, BeoCenter 2 included features and interfaces that were not utilised, but only will be utilised in future products. This was done to ensure re-use of the existing standard designs. It is worth noticing that the future standard designs were not developed yet, but they were specified to a degree where all key components (e.g. micro processor), interfaces and features were known. Hereby, the existing standard design could be prepared for these features and interfaces.

Design units – Not everything was standardised and re-used at Bang & Olufsen. That would limit the ability to launch innovative products. The design units that were not standardised were displays, keyboards, movable mechanics, etc. These were not standardised as these would vary due to the industrial design of the products. However, their interfaces to the standard designs were standardised in order to ensure re-use of the standard designs. Bang & Olufsen has several products that include hard drives. As described previously (Page 79) these hard drives has not been standardised and does not comply with the rules of standard design definition: Decision of re-use, documentation and responsibility - as it is prescribed in “Standard design” (Page 79).

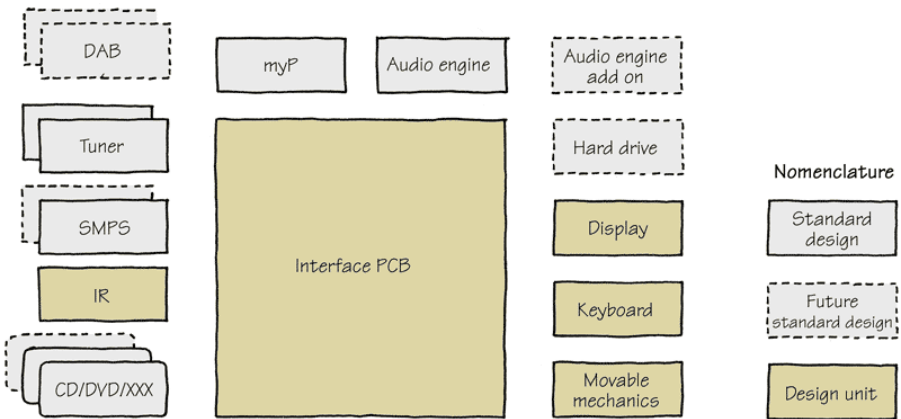


Figure 87. Schematic representation of a family architecture in the audio portfolio at Bang & Olufsen. One product family has been launched based upon this architecture and two other families will be launched in the near future.

Modelling the family architecture

The following includes the modelling formalism that was applied at Bang & Olufsen. The formalism was based upon the functional modelling formalism described earlier (Page

101). The objective of an architecture model is to model the elements of an architecture, i.e. standard designs, design units and interfaces. The diagram included standard designs that were available as well as new coming standard designs. The existing standard designs would of course be more detailed than the new coming standard designs.

The family architecture of BeoCenter 2 is shown in Figure 87. Each block represents a design unit or standard design. The following nomenclature is applied:

- Existing design units
- Future design units
- Existing standard designs
- Future standard designs
- Surroundings

Variety is marked with blocks that were placed on top of each other with a little offset, e.g. FM-tuner (Figure 87). Figure 87 does not include the interfaces. A more detailed model was needed for showing the interfaces. Figure 88 shows a more detailed model of the family architecture. The contents of the model have been blurred in order to hide confidential information. However, the model in Figure 88 gives an impression of the level of details in family architecture.

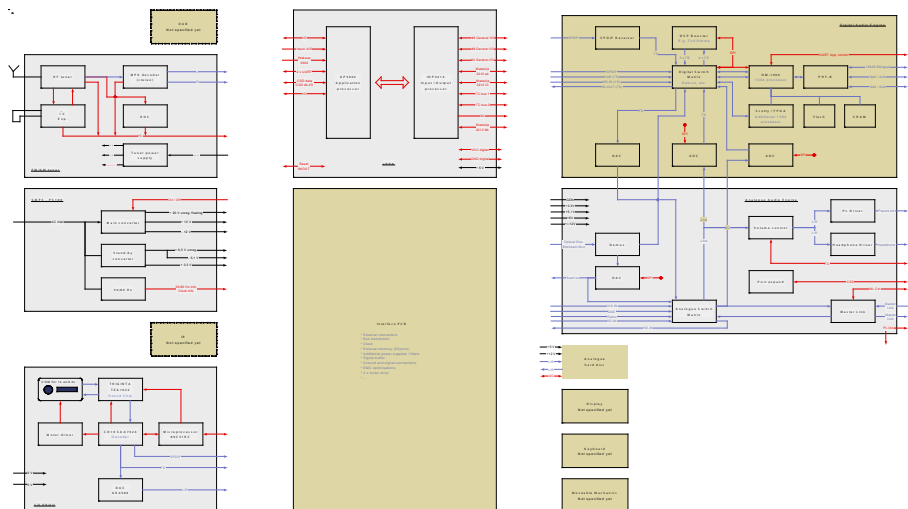


Figure 88. Family architecture for the audio portfolio at Bang & Olufsen, 2005. The model is identical to the model in Figure 87, but more detailed here.

A shaded block (■) in the architecture model represents a standard design, Figure 89. If the standard design was not fully designed yet it was represented with a dashed block (■) otherwise a full-drawn line was used. In some cases it was helpful to detail the standard design a little in order to make the architecture diagram easier to communicate. In case of need for more details, the standard designs were decomposed into 2 to 10 functional blocks. The functional blocks were also represented with blocks. Non-re-usable functionalities (i.e. design units) that are not a part of any standard designs, but were included in the architecture, were illustrated with a block with light brown background (■).

It is noticed that the model in Figure 88 includes electrical interfaces among the existing standard designs, future standard designs, existing design units, future design units and the surroundings.

Figure 89 includes a nomenclature for the architecture diagram that was applied at Bang & Olufsen.

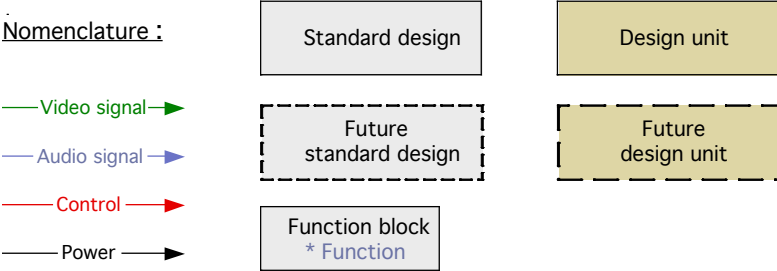


Figure 89. Nomenclature for architecture diagrams and standard design diagrams applied at Bang & Olufsen.

The interfaces between each unit were drawn with lines. When modelling architectures the following types of interfaces were applied at Bang & Olufsen:

- *Electric interfaces* – Control, power, signals (e.g. audio and vision), etc.
- *Mechanical interfaces* – Geometric support, flow of material (e.g. hydraulics), heat, cooling, power/movement, etc.
- *Software* – Registers, device driver, protocols, etc.

In principle a line was drawn for each interface in the architecture. But for complicated electronic products that would have meant hundreds or even thousands of lines. In such cases the architecture diagram was simplified by only drawing one line for each type of interfaces between the individual standard designs. For example if two standard designs had 3 control, 5 audio and 2 power signals between each other, this would be drawn as one control, one audio and one power line. Further details were documented in the documentation of each of the standard designs (Page 145).

The technique for modelling architectures is relatively simple. Experiences from Bang & Olufsen and other industrial projects show that it takes weeks or months to create a meaningful diagram. It is seldom that a company has one person, who has the needed insight to draw the diagram. Therefore several domain experts have to be involved in drawing the diagram and afterwards several reviews with domain experts are needed to get the architecture diagram approved.

One of the key arguments for introducing standard designs and architecture is to enhance re-use of standard designs across product families and hereby lower the resources for bringing new products to the market. In the Bang & Olufsen case, the BeoCenter 2 was the first product to benefit from existing standard designs and the family architecture. So far, the audio portfolio at Bang & Olufsen includes two other product families that will be derived from this family architecture. The first product is currently under development. The three product families being developed upon the described family architecture are schematically illustrated in Figure 90. The illustration shows what part of the family architecture they utilise.

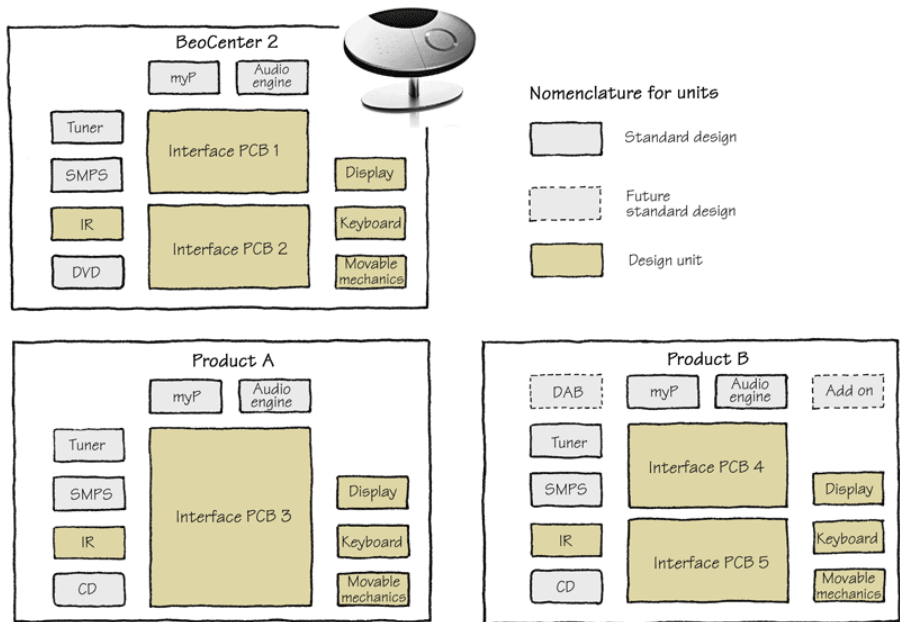


Figure 90. Top left: The family architecture of the BeoCenter 2. Bottom left and right: Two product families that are currently being developed. All three families are based on the family architecture shown in Figure 88.

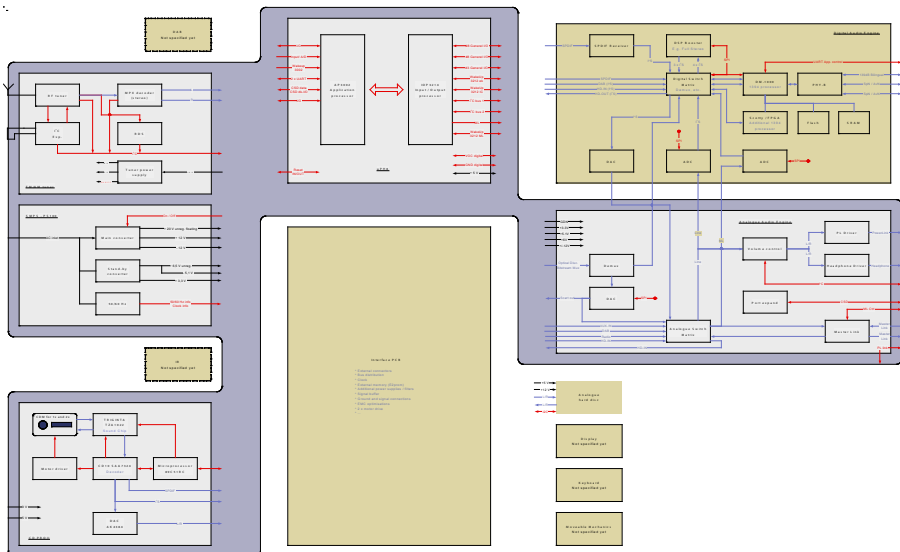


Figure 91. The blue standard designs are the family platform for the BeoCenter 2. This family platform is based on the family architecture shown in Figure 88.

The family platform

A platform is modelled in similar ways as an architecture. As described previously a platform is an instance of an architecture that only includes the existing standard designs and interfaces (Page 85). In the BeoCenter 2 case the platform was the standard designs that this

particular product family utilised.

The standard designs that are highlighted with blue in Figure 91 are the family platform that was realised with the BeoCenter 2.

17.5 The first standard designs at Bang & Olufsen

The introduction of standard designs at Bang & Olufsen has influenced on the working patterns within the R&D department. Some people have been appointed “standard design managers”. These people have the responsibility of specifying, developing, implementing and maintaining the standard designs. To do so, two tools were implemented. One of the tools was the one used for modelling the organ structure as prescribed in “Tool: Generic organ diagram” (Page 100). This tool is similar to the tool applied for modelling the family architecture and platform for the BeoCenter 2. The following describes how the generic organ diagram has been applied for modelling standard designs. This description is followed by a description of a tool that has been applied for documenting the design rules related to implementation of standard designs. This tool is denoted a *standard design document*.

The organ structure of a standard design

The model of the organ structure of a standard design follows the principles and nomenclature that is described in “Tool: Generic organ diagram” (Page 100). The main difference is the level of details (Figure 92). The blocks in the model are either key components (micro-processor, gear, etc.) or an encapsulation of organs. A rule of thumb says that there should be 8 to 10 blocks in a standard design. Each block is given a name. Listing functionality of the block can be very useful for products that have distributed functionality among the standard designs, which sometimes is the case for microprocessors.

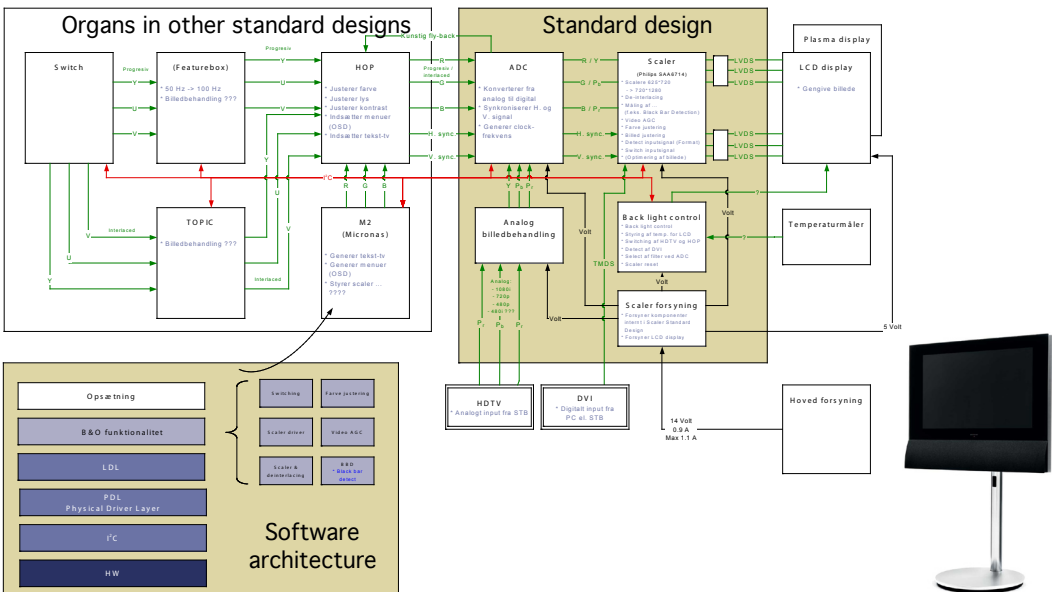


Figure 92. An example of a standard design diagram for a television “scaler” from Bang & Olufsen. The scaler scales the resolution of the vision signal to match the resolution of the LCD or plasma screen. The scaler is implemented in the television BeoVision 6.

The main interfaces between the blocks within the standard design should be drawn with lines. But what is most important is the modelling of the interfaces between the standard designs and the interfaces between the standard designs and other functional blocks. ALL interfaces should be represented. The interface should not have any loose ends. This means that standard designs and blocks that are indirectly in contact with the concerned standard design should be modelled as well (Figure 92). Otherwise, it will be hard to understand the necessity of the individual interfaces.

Tool: Standard design document

In order to enable re-use of standard designs it is necessary to document these. A *standard design document* is a documentation of the standard design, which gives the engineers and the industrial designers that re-use the standard design the knowledge of what the standard design can do (functionality) and how to implement standard designs (interfaces and guidelines). It does not include all details, but it has references to experts and further documentation (protocols, standards, etc.). It can be compared to a technical specification and data sheet that you can order from a supplier. The size of the document is 5 to 10 pages. In the following, the headings of the standard design document are described.

The front page of a standard design document includes all the traditional formalities, e.g. date, author, version, status, etc. The front page also includes an abstract and a picture/drawing.

The next heading gives an overview of the functionalities provided by the standard design. The functionality is the answer to the questions “What does the standard design do?” and “How does it perform?”. In some cases it might be helpful also to describe functionality that is NOT supported by the particular standard design, e.g. a CD standard design that does not support MP3-files.

The document includes a *generic organ diagram* of the standard design diagram. If the diagram is large and complicated, a simplified version is made together with a hyperlink to the original. Similar to the electrical and mechanical diagrams a software diagram can be included. If the standard design includes a substantial amount of software, that is, beyond device driver level, the architecture of this software should be described. This description should also include the intended context for use of the standard design and the interfaces exposed by the standard design for use by the surrounding software. The software description should depict the exposed interfaces and describe the major components of the application included within the standard design.

The document includes a list of all *electrical interfaces*. Each interface is described individually by: Name, interval, unit and connector. Interfaces that are clearly defined by standards (e.g. USB 2.0) are only defined in this document by its name. When describing the characteristics of an interface it might be beneficial to consider not only standard use, but also standby, sleep mode, power up, etc. One should remember that a standard design might include electric interfaces that are only of interest to other standard designs, e.g. power or signals can be distributed through a standard design.

A standard design may provide *software interfaces* on different levels of abstraction. If more than one interface is available, this enables re-use of the standard design at different levels seen from the application software. The lowest level is setting of register values. This interface is implemented on the standard design. The device driver interface is implemented in

the main microprocessor and hides the I²C protocol for the user. The application interface is implemented in the main microprocessor based on the device driver interface. It provides more advanced functionality based on the capabilities of the standard design. In some cases all interfaces may be implemented in the standard design and access is offered only to the highest level interface typically by means of a high level protocol such as a Source Link Protocol.

Electrical-software interfaces - If the electrical components of the standard design require initialisation and offer functionality accessible by software, the registers to enable this have to be enumerated. This includes documentation for register values, relevant addresses and possible timing constraints. Each register and the allowed values of these are described. If combinations of register values are required to access functionality, or change the state of the hardware, these combinations are described in detail. If the hardware imposes any timing constraints on accessing or setting register values, these are described. If any initialisation or default values have to be set, these are also described. This also includes possible requirements regarding the order of initialisation.

The standard design document also includes implementation rules or guidelines for implementation of the standard design. Such design rules describe how the surrounding system (i.e. product) has to be designed in order to utilise the standard design. The design rules may also describe how the standard design can be modified in order to be implemented in a product.

Experiences from Bang & Olufsen have shown that it takes 4 to 8 hours to create the documentation as long as it is just a matter of documenting and not developing or doing research. This documentation has great value for the engineers who re-use a standard design and those who carry out maintenance. The first versions of the standard design documentation was created as Word documents, but in the latest versions the standard design template has been integrated into the PDM-system as a formal way of documenting standard designs.

17.6 The current status at Bang & Olufsen

Having read the case about Bang & Olufsen in this work, one may think that everything is re-used at Bang & Olufsen, but that is not the case. Standard designs that would limit the ability to be innovative, either from a technology or industrial design point of view, would never be a success at Bang & Olufsen. The challenge is to make the standard design as flexible as possible and to make the assortment and family architectures long lasting and applicable for future technologies.

All new products at Bang & Olufsen are not based on re-used standard designs. A product project is free to develop a new product without re-using the standard designs. That is the case if industrial design offers too little space for the existing standard designs, or the product needs functionality that is not offered by the assortment architectures, family architectures and the standard designs. The consequence is, however, that the product project will have to develop everything from scratch and that will be time and resource consuming.

The current status at Bang & Olufsen is that a family architecture for audio exists ("The family architecture that BeoCenter 2 is based upon", Page 139) and that the first product has been launched (The BeoCenter 2). This audio family architecture also includes future products, meaning that the next three audio products will be based upon this family architec-

ture. Also, this family architecture includes new standard designs with new technologies and features that have not been fully developed yet. Four of the standard designs from the audio family architecture are developed in agreement with the described activities; also they follow the documentation guidelines as described earlier ("Tool: Standard design document", Page 145). Three new audio standard designs are in progress of final documentation. Family architectures and standard designs for vision (i.e. television) and phone are still under development.

Some of the standard designs have proven their worth to such an extent that they have been implemented in products that are not even based on the existing family architecture. Figure 93 shows the existing standard designs, their revisions and the product that utilises the standard designs.

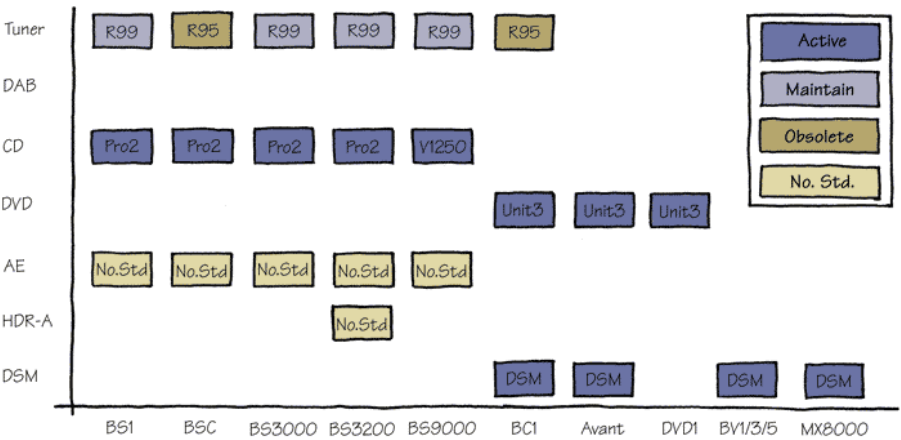


Figure 93. The vertical axis shows the existing standard designs. The horizontal axis shows the existing products that utilise these standard designs.

Future products will also utilise these standard designs, but also new ones will be introduced. This is outlined in Figure 94 together with some of the new products that will utilise these standard designs.

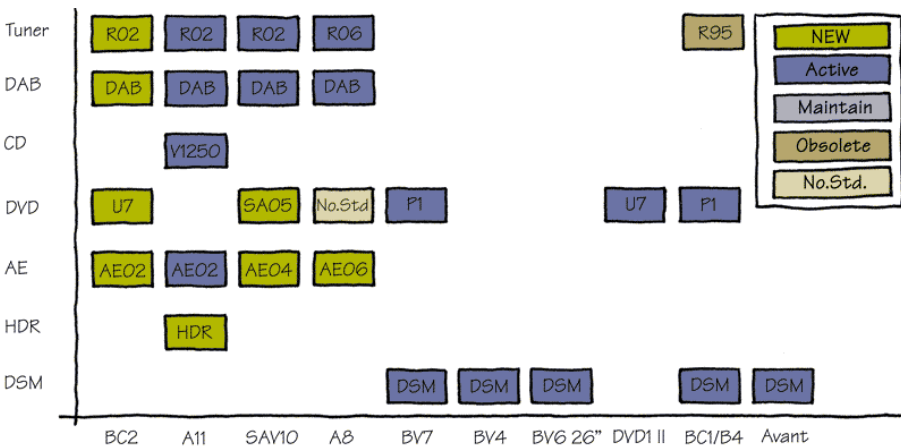


Figure 94. The vertical axis shows the existing and new standard designs. The horizontal axis shows the new products that utilise these standard designs.

17.7 The role of this research at Bang & Olufsen

The role of this research at Bang & Olufsen has been to explore the concepts of architecture and standard designs in order to understand the nature of the concepts and to apply them. The application aspects of the concepts have primarily been addressed by means of developing the models and tools described in Part 3, Part 4 and Part 5 and by applying them in projects. Participation in projects and giving courses has played an important role for handing over the results of this research to the organisation.

The models have been developed in dialogue with R&D staff and staff from the Method department at Bang & Olufsen. Especially, an R&D manager from the audio business area and managers from the Method department have been active in the process of creating the tools and models.

The tools and models were typically proposed to R&D staff at an early stage. Hereafter, R&D staff commented on the tool or model and suggested improvements, which were implemented. Subsequently, a tool or a model was created for a given product family. These tools and models were typically created in collaboration with R&D staff. After a number of improvements of the tools and models the R&D staffs adapted the tools and models and took responsibility for applying the tools and models. The tools and models in Part 3, Part 4 and Part 5, which illustrate Bang & Olufsen products, are all results of projects carried out at Bang & Olufsen as a part of this research.

The issues concerning organisation, project management, etc. have not been within the scope of this project.

Application of models in the audio business

The audio business area is the business area that first adapted tools and models. Today the tools and models related to standard designs are an integrated part of the design process of standard designs. The models are considered a part of the final documentation for a standard design.

The family architecture that the BeoCenter 2 is based upon is the first family architecture created at Bang & Olufsen. The next audio product will also be based upon this architecture and it is likely that one audio product more is based upon this family architecture. But it is not clear how the family architecture will be developed further and by whom.

The reason that the audio area has been early adapter of the models is due to personal motivation among the R&D managers within this business area. But two other factors also play a role. The audio business area has with success been able to standardise a few subsystems (e.g. FM-tuner) before the concepts for standard design and architecture were introduced. It might also have played a role that the audio products are "less complex" than the vision products and therefore it might seem easier to get started with implementation of standard designs.

Application of models in the vision business

The tools and models proposed in this research were also applied in the vision business area. Several standard designs have been defined and documented. These standard designs typically encapsulate new functionalities (e.g. DVD) that are added to existing vision products. The old functionalities are not decomposed into standard designs yet. This is due

to the amount of resources needed to do so. It would demand a total re-design of the electronics and software of the vision products.

An attempt has been made to design a family architecture for the vision portfolio. But the project was put on hold because it has been decided to postpone the re-design of the vision products. The new vision products will be based on the existing electronics and software with a few new standard designs that have been added.

Improvement areas

Currently, a number of standard designs exist and new ones are developed. This process is likely to continue due to the enthusiasm within the standard design organisation. However, only one family architecture exists.

The application of family and assortment architecture at Bang & Olufsen is not clear yet. It is discussed who should develop the architectures and who should have the responsibility for the architectures. It is not a commonplace decision to make because it disposes for the business at Bang & Olufsen.

One engineer stated *"The R&D director should sleep with the assortment architecture under his pillow"*. The point is that an assortment architecture is so important that it should not be handed over to a random picked engineer to have responsibility for the assortment architecture as it disposes for the business at Bang & Olufsen.

With the current product strategy at Bang & Olufsen and the wish to re-use standard designs, it seems natural to take the next step and integrate the development of the architecture within the R&D department. The new products and new features will include more advanced network functionalities and an architecture is a tool for "managing" the development of such functionalities for an entire product portfolio.

The generic organ diagram has been applied for modelling architectures and standard designs. In both cases the diagrams have been applied with success. This implies that the generic organ diagrams have been able to model some major decisions. Especially decisions related to the structure and interfaces have been modelled with success.

It is relatively easy to draw a generic organ diagram as long as it only has to document the organs and interfaces. However, it is more time consuming, if the architecture and the standard design are not designed yet. In such cases the models cannot be more detailed than the decisions made on the architecture or the standard design.

The standard design document (Page 145), which is applied for documenting design rules for implementation of the standard designs, has been integrated into the PDM-system at Bang & Olufsen. It has become a standard for documentation of standard designs. All standard designs are documented in this format. One of the ongoing discussions is related to the level of details in this documentation. Some argue that the new type of documentation is already documented in other documents. However, it has been decided to hold on to the new type of documentation in order to ensure uniform documentation of all standard designs. To avoid duplications of the documentation, the standard design documents refer to each other by means of hyperlinks.

Both the generic organ diagram and the standard design document include documentation of the interfaces. Two issues related to interfaces are discussed from time to time:

- *Level of details of the interfaces* – The interfaces can be more or less detailed in their specification and documentation. It has been chosen not to detail the interfaces more than what has been described in Part 4 and Part 5. The interfaces are documented in more detailed in CAD models, printed circuit board models, etc.
- *Ownership of interfaces* – The ownership of the interfaces has been discussed frequently. This means, who has the responsibility for specification, development, documentation and maintenance of the individual interfaces. This discussion was identical to the discussion described in “Ownership of interfaces” (Page 88). Bang & Olufsen has chosen an approach, where the responsibility and ownership of the interfaces is appointed to the owners of the standard designs. This is done because the ownership of the individual standard designs is clearly defined in the organisation. The disadvantage is that the ownership is distributed among several standard designs.

17.8 Conclusions on the changes at Bang & Olufsen

The above illustrates how Bang & Olufsen applies architectures and standard designs. It has changed the way Bang & Olufsen develops products. This research has been an active part of the changes at Bang & Olufsen. The following concludes on how the results from this research have affected the way Bang & Olufsen develops products:

- *Design preparations* – One of the central points related to the concepts of architecture and standard design is the focus on developing solutions that are planned to be re-used. This implies a more proactive approach for developing of subsystems that are re-used. Today, Bang & Olufsen has a standard design organisation, which has this as their primary task along with the development, implementation and maintenance of the standard designs.
- *Re-use of architectures and standard designs* – One of the products on the market is based on a family architecture that follows the definition formulated in Part 3 and other products are being developed at the moment based on this family architecture. Likewise, several products include standard designs. These standard designs are developed in agreement with the family architecture.
- *Documentation* – The tools and models formulated in Part 3, Part 4 and Part 5 have been adapted by the Bang & Olufsen standard design organisation as a formal way of documenting architectures and standard designs.
- *Re-use of knowledge* – A central part related to re-use of architectures and standard designs is the re-use of knowledge. A part of this knowledge is encapsulated in the elements that are re-used by means of standard designs and their documentation. However, knowledge is also re-used by having staff that dedicate their time to the standard designs. This implies that these people become experts in implementation of these standard designs.

This chapter along with the examples in Part 3 show that the concepts of architectures and standard designs have been applied at Bang & Olufsen. It also shows that Bang & Olufsen has changed their way of developing products. The changes have led to drastic benefits for Bang & Olufsen:

- *Reduction of time-to-market* – Bang & Olufsen claims that they have reduced the time-to-market for new products. Five years ago, a typical development project took 2 to 4 years

to develop. Today, only 1 to 2 years are need. This reduction is achieved without adding extra R&D resources.

- *More product launches* – The reduction in time-to-market enables Bang & Olufsen to launch more products to the market than ever before. Previously, Bang & Olufsen was able to launch at most one television every year, but in 2004 Bang & Olufsen were able to launch three new televisions to the market, i.e. BeoVision 4, BeoVision 6 22" and BeoVision 6 26".

This chapter did not quantify the benefits from the application of architectures and standard designs. This is shown in the chapter to follow.

18 Bang & Olufsen case: Reducing R&D resources by means of re-use

Cases in the literature reveal that re-use of platforms can have great impact on the business of a company and the ability of the organisation to introduce new products to the markets. Examples of such successful applications are VW (Page 44), Sony (Page 46) and Philips Consumer Electronics (Page 47).

Over the latest five years much, focus has been on developing and re-using standard designs at Bang & Olufsen. Several standard designs have been developed and are implemented in several products. Examples are FM-tuner, DVD, Power supply (SMPS), CD, Audio engine, Audio micro processor (μ PH8), etc. These implementations provide an opportunity to measure and evaluate the benefits from re-using standard designs.

The objective of this chapter is to quantify the R&D resources saved as standard designs are re-used and the resources that are saved, when standard designs are updated. The starting point for these estimates is the standard designs applied in the audio portfolio. The estimates are exemplified by means of completed projects (BeoCenter 2 and DVD) and ongoing projects (product-A11).

18.1 Saving 15% of the R&D resources on developing product-A11

One of the new audio products currently under development is denoted "product-A11". This product is from a functional point of view similar to other Bang & Olufsen audio products. Fortunately, previous projects have developed standard designs that include some of these functionalities. Consequently, product-A11 can re-use these standard designs.

Table 8 includes an estimate of the R&D resources ("man-months") that will be saved by re-using existing standard designs. The standard designs that will be re-used are Audio engine, CD, FM-tuner, DAB and Audio micro processor (μ PH8). The column "Re-use of standard designs" lists the R&D resources needed to integrate a given standard design in product-A11. A rule of thumb says that it will take 2 to 3 man-months to integrate a standard design into a product. These resources will be spent for optimising and adjusting the product to the standard design. NO changes are made in the standard design. Otherwise, at least 10 man-months would be needed.

Table 8 also includes the estimated R&D resources for developing a new Audio codec for

SD cards (software resources are not included). An SD card is a memory card for recording music on, e.g. MP3. Table 8 also indicates that an audio micro processor will be re-used, but data is not available for estimating the resources related to this standard design. However, considerable R&D resources can be expected to be saved from re-using the audio micro processor. All together, 33 man-months were estimated (planned) for integration of the mentioned standard designs.

	Re-use of standard designs	Re-use of knowledge	No re-use
Standard design: Audio engine	3		18
Standard design: CD-engine	3.5		12
Standard design: FM-tuner	1.6		20
Standard design: DAB	5		15
Standard design: Audio codec (New)	19.9		19.9
Standard design: Audio micro processor	-		-
Integration of standard designs	33	60	85
Other development within product-A11	253	253	253
Total development of product-A11	286	313	338
Total savings [Man-months]	52	25	0
Saving in the standard design organisation [%]	61	29	0
Total savings in the R&D department [%]	➡ 15	7	0

Table 8. Product-A11 re-uses five standard designs. The R&D resources that will be saved are included in the table. The R&D resources are estimated as “man-months”.

The column “No re-use” in Table 8 states the R&D resources needed if no standard designs exist and if no re-use is possible. These figures were based upon actual figures from development of the individual standard designs. The column “Re-use of knowledge” is a rough estimate of the R&D resources that will be needed if the standard designs cannot be re-used physically.

Based upon the above estimates and the estimate of the total amount of R&D resources expected to be needed to develop product-A11, it was possible to estimate the savings. All together, at least 52 man-months can be saved by re-using standard designs. This implies that about 61% of the R&D resources that will be provided by the standard design organisation can be saved. Totally, 15% of the R&D resources can be saved for product-A11.

18.2 Saving 14% of the R&D resources if the BeoCenter 2 was based on standard designs

The previous example shows the R&D resources that were expected to be saved for a new product. The following includes an estimate for a product (the BeoCenter 2) that was launched in 2004. The BeoCenter 2 was not based on existing standard designs, but the project was used for developing the standard designs soon to be integrated in product-A11. The purpose of the following estimate was to illustrate the potential savings, if the standard designs had existed as the BeoCenter was developed.

The BeoCenter 2 was utilised for developing the following standard designs: FM-tuner, Audio engine, SMPS100 and Audio micro processor (μ PH8). Table 9 includes an estimate of the R&D resources that were used for developing these standard designs. Table 9 also includes an estimate of the resources needed, if the standard designs already had existed and only should be integrated.

	Re-use of standard designs	No re-use
Standard design: Audio engine (New)	3	18
Standard design: DVD-engine (New)	10	12
Standard design: FM-tuner (Updated)	3	24
Standard design: Power supply (New)	3	18
Standard design: Audio micro processor, µPH8	-	-
Integration of standard designs	19	72
Other development within the BeoCenter 2	299	299
Total development of the BeoCenter 2	318	371
Total savings [Months]	0	53
Saving in the standard design organisation [%]	0	74
Total savings in the R&D department [%]	0	14

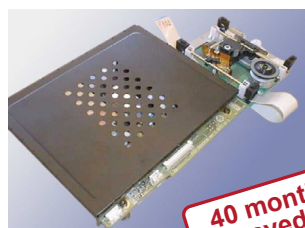
Table 9. Four new standard designs were developed for the BeoCenter 2. The table includes R&D resources that would have been saved if the BeoCenter 2 was based on existing standard designs. The R&D resources are estimated as "man-months".

The estimate in Table 9 was made identically to Table 8. The only item that needs further comments is the DVD. This particular standard design already existed; however due to the industrial design of the BeoCenter 2, the standard design was modified in order to fit into the BeoCenter 2. These modifications were only related to the physical size and shape of the standard design and not to any changes in the DVD functionality.

Based upon the above estimates and the estimate of the total amount of R&D resources needed to develop the BeoCenter 2, it was possible to estimate the savings. The savings that would be achieved, if the BeoCenter 2 was based on existing standard designs, was 53 man-months. This implies that the standard design organisation could have saved 74% of their resources and the project could have saved 14% - totally.

The BeoCenter 2 case reveals that savings that will be achieved by product-A11 also could have been saved for the BeoCenter 2 had the standard designs existed.

- 18 months development for DVD standard design for Avant
- 6 months implementation for DVD1, BeoVision 7 and BeoCenter 1
- Note: The figures only include standard design resources



40 months saved!



Figure 95. The DVD standard design was updated from a Philips solution to a Pioneer solution. The re-use of standard designs saved 40 man-months.

18.3 Saving 40 man-months on updating the DVD standard design

The primary goal of introducing standard designs at Bang & Olufsen was to reduce the R&D resources needed for developing new products. In the following it is illustrated how standard designs also have significantly positively influenced maintenance and update of products.

The latest update of the DVD standard design is the object for illustrating the benefits from standard design application - seen from a maintenance point of view. In this case, the DVD standard design was updated by changing the key-components and software from Philips to Pioneer. These changes were implemented in four products: the Avant DVD, the DVD 1, the BeoCenter 1 and the BeoVision 7 (Figure 95).

18 months were spent on re-designing the DVD standard design for the Avant DVD. The DVD 1, the BeoCenter 1 and the BeoVision 7 utilised the exact same standard design. The new DVD standard design was therefore relatively easy to integrate into these products. 2 months were spent for each implementation of the standard design. If dedicated solutions were made instead, approximately 18 months would have been needed instead for each implementation. All together about 40 man-months were saved in this case. This estimate only includes the R&D resources that were spent in the standard design organisation. Additional resources were spent on updating the products and the assembly, but that would not influence the above savings.

Another benefit related to maintenance of standard designs is that the standard designs are relatively well-documented, i.e. "Tool: Standard design document" (Page 145). This documentation eases the maintenance.

18.4 Abstract re-use of standard designs

As the above cases were analysed, it became clear that physical re-use of standard designs was most beneficial. The metaphor "showcase" (Danish "vitrineskab") was often used as a metaphor for re-use of standard designs on different levels, i.e. physical re-use, re-use of PCB layout, re-use of diagram, re-use of specification, etc. (Page 81).

The principle of different types of re-use was valid. However, it was clear that physical re-use of mechatronics is most beneficial. Physical re-use meant re-use of a standard design without changing the standard design at all. When a standard design was physically re-used, it took 2 to 3 man-months to implement the solution into a product. These resources were used on optimising and adjusting the product to the standard design. Only substitution of the electrical components was possible, but besides that no changes were made in the standard designs. As soon as a change was made in the PCB, the PCB layout had to be verified. Typically, 3 verifications were needed and that would take at least 10 man-months.

Therefore, physical re-use of a standard design was desirable when possible. However, other levels of re-use can also be beneficial, but one should be aware that even small changes in the PCB add at least 10 man-months to the integration.

18.5 Generalising the savings to the entire audio portfolio

One may ask whether the above savings were representative for the Bang & Olufsen portfolio? First of all, the cases presented here were real and not speculative. Secondly, several

standard designs existed. These standard designs were integrated in several products as illustrated in Figure 93. Therefore, the savings outlined in the above were achieved.

New standard designs and updates of the existing standard designs were planned. Figure 94 illustrates that these standard designs will be integrated in new products. It is therefore reasonable to expect that the savings that are outlined in the above also can be achieved in future products.

Having stated that the savings can be expected to be saved in future products, it is also important to state that not all future products will be able to benefit from the standard designs. One reason is that the industrial design might not allow re-use of the standard design due to the physical size of the product. Another reason is that new products might include radical new functionality that is not convertible with the existing standard designs.

18.6 Data and method for quantifying saved R&D resources

The estimates in this chapter were all carried out by Martin Rasborg (Standard Design Manager, Audio Business) and processed by Ulf Harlou.

Product-A11 – The R&D resources, which were estimated for developing product-A11 (Page 151), were based upon the resources that were assigned to the tasks. The figures that formed the basis for developing product-A11 without standard designs were all gathered from the actual figures that were used for developing the individual standard designs in previous projects.

BeoCenter 2 – The figures for developing the standard designs in the BeoCenter 2 (Page 152) were the actual figures. The estimate for developing the BeoCenter 2 based on standard designs was estimated based on the figures from product-A11.

DVD – The estimated R&D resources related to the DVD update (Page 154) were based upon actual figures from the Avant DVD, the DVD 1 and the BeoCenter 1. The BeoVision 7 integration was not completed at this stage and figures were therefore based on experience from the other products.

Prejudice: It takes longer to develop standard designs – Experience from the audio standard design organisation revealed that no extra R&D resources were needed for developing a standard design. Developing a dedicated solution was not easier. Even though it was prescribed that standard designs must be documented according to a new set of “rules”, it did not increase the time consumption. The extra documentation took about 1 day. If it took longer to develop a standard design, it would be caused by unclear specification of functionality in future products.

Prejudice: A standard design is expensive – It was often stated that standard designs were more expensive than dedicated solutions. Experience from the audio standard design organisation indicated that the direct cost of the individual standard design increased by about 5%. Note: It was not the entire product that became 5% more expensive, but only the standard design. These extra costs were caused by extra interfaces and extra functionalities that might not have been needed for dedicated solutions. It is the authors’ belief that these extra costs were insignificant compared to the benefits.

18.7 Conclusions on reduction of R&D-resources at Bang & Olufsen

The chapter included estimates of the benefits that were achieved by re-using standard designs. It was shown that a 15% reduction of R&D resources was achieved for developing audio products that were based on existing standard designs. The reduction might even have been larger due to re-use of Audio micro processor (μ PH8) that was not included in present estimates. The reduction was of course depending on the functionality of the product and the industrial design.

The chapter also showed that maintenance benefits from re-use of standard designs. The DVD case showed that 40 man-months were saved. Several people at Bang & Olufsen pointed out that another major benefit from re-use of standard design was the reduction of risk. When standard designs were re-used the risk that the standard designs did not function properly was very small. This chapter has not quantified the risk benefits.

From benchmarking with Philips Consumer Electronics (Page 47) it is learned that they have become four times faster at bringing new products to the market by means of re-used standard designs. Such a reduction is probably not possible for Bang & Olufsen due to the importance of the industrial design. It is safe to conclude that a 15% reduction of R&D resources was satisfying. The reduction was achieved without compromising the innovative industrial design. It is the ambition of Bang & Olufsen to achieve further savings in the R&D resources needed for development of new products.

This chapter only focuses on audio products and no attempts have been made to generalise the findings to vision or phone products.

19 Vestas case: Enhancing parallelism of development activities

The results from this research have been applied at Vestas Wind Systems. The objective of introducing this case is to illustrate how application of architecture can enhance the degree of parallelism among development activities.

19.1 Architecture and interfaces are central for running parallel developing activities

Vestas manufactures wind turbines, which turn wind energy to electricity. Key figures for today's wind turbines are 3 MW, 200 tons, 130 m tall, 100 m diameter rotor, 10,000 components (excl. electrical components). Vestas was currently developing the next generation of wind turbines, which would be larger. Due to confidentiality the new generation of wind turbines is made anonymous.

The goal of the project was to provide a model of the family architecture. The model should document the current state of the architecture. This implies that it should include all standard designs and their interfaces, or at least those that were defined at the current state of the project. Figure 96 includes a model of the family architecture. The blocks in the model represent standard designs. The standard designs are connected by means of interfaces. For wind turbines of such a size and complexity one person could not be up-to-date at all

times with all the details.

The model of the architecture should form basis for documenting the architecture and for managing the responsibilities of the individual standard designs and their interfaces. The model was completed in similar ways as for the Bang & Olufsen cases.

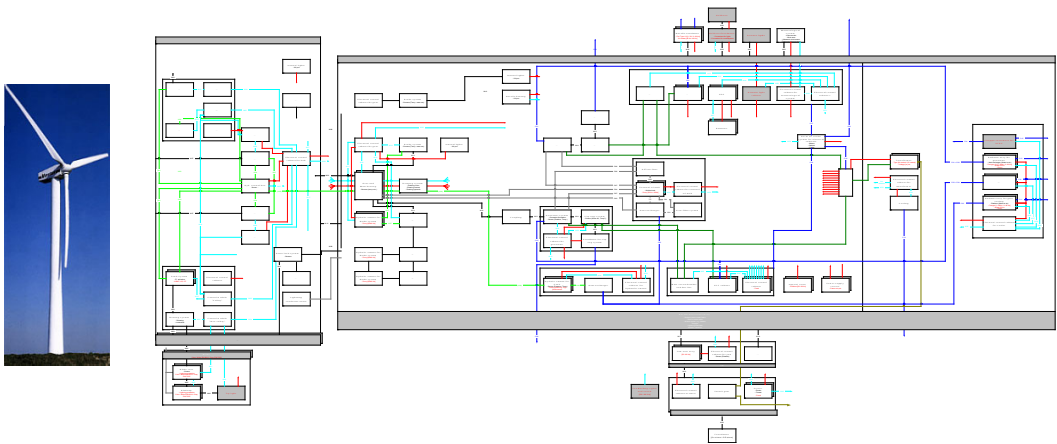


Figure 96. A model of the family architecture of the next generation of Vestas wind turbines. Confidential aspects of the architecture have been removed as the turbine has not been launched yet.

The model has proven its worth for distributing responsibilities of development activities. The model was applied by the management and the project leader for visualisation of responsibilities of standard designs and interfaces. It was applied for making decisions on:

- Who has the responsibility for what standard design?
- Who has the responsibility for what interface?
- What standard designs are connected and who should coordinate with whom?

To enable this each, standard design was labelled with an “owner”. Likewise, each interface was labelled with the owner. The owner of a given interface or standard design also had the responsibility of coordinating his development activities with standard designs that interface with his interface.

The clear distributed responsibilities enabled the project leader to run the development activities within the project in more parallel than what had been possible in previous projects. The R&D resources saved have not been quantified due to two factors. One, the project was not completed yet. Two, it was difficult to compare this project with others because the project also included development of radical new technologies. This management system of interfaces and standard designs were considered essential for running the development of the standard designs in parallel.

19.2 Conclusions on Vestas’ enhancement of parallelism among development activities

The Vestas case illustrated how the concept of architecture and models of architecture enabled Vestas to capture the family architecture of the next generation of a wind turbine fam-

ily. The project at Vestas also showed that it was possible by means of an architecture model to capture who had the responsibility for the individual standard designs and interfaces. This eased the coordination among the development activities of the standard designs, which again enabled development of the standard designs in parallel.

20 Conclusion on industrial applications of architectures for product families

The industrial applications of the concepts of architecture and standard design have proven that it is purposeful to apply the thinking pattern and the models and tools from Part 3 and Part 4. Industrial applications in Part 5 showed that benefits can be obtained from applying the contributions of this research. The benefits achieved from these applications were:

- A higher degree of re-use of solutions, i.e. standard designs
- A higher degree of re-use of knowledge from implementation of standard designs
- Proactive re-use, i.e. re-use was planned several product generations ahead
- Documented re-use
- Easier to update products based on standard designs
- Reduction of R&D resources
- Reduction of lead-time
- A higher degree of parallelism in development activities

Conclusions on industrial applications of the theoretical contributions

The theoretical contributions of this research have been applied in industry by means of the models and tools. The insights in the phenomena of architecture and standard design have been useful in the dialogues with companies. The insights in the phenomena have especially been useful in the dialogues concerning:

- Why introduce architectures and standard designs?
- How to work with architectures and standard designs?
- How to model architectures and standard designs?

The concept of architecture is meaningful as a description of how to develop product families. It is useful for describing how to re-use standard designs in several products or product families. Also, the concept of architecture has proven to be meaningful for managing how several products are built upon the same structure.

The concept of standard design has also proven to be meaningful. It emphasises on the importance of distinguishing between the parts of the product family to be re-used and those that should not be re-used. Engineers who adapt the idea of re-use, tend to want to re-use “everything”. But it is just as important to be aware that not everything can or should be re-used.

One of the challenges when designing architecture is to deal with features that should be implemented “some time” in the future. For such features it is often unclear, when they will

be implemented, how they should be implemented, etc. The distinction between future and existing standard designs/design units enables discussions on this problem. The explicit models of architectures and standard designs support this problem.

One of the aspects that needs further investigation is the classification of interfaces. The concepts of standard design and architecture include the interfaces as a central part. The research also suggests how to model these. But there is a need for further investigation of the phenomenon, e.g. how are spatial interfaces of an architecture illustrated?

The introduction of standard designs and architectures in an organisation introduces new working patterns, new roles new responsibilities, etc. The Bang & Olufsen case ("The new design processes", Page 135) suggests some of the organisational and process mechanisms for dealing with the new concepts. But it could be beneficial to investigate the organisational mechanisms further.

It is concluded that theoretical contributions of this research have been applied with success in several industrial applications.

Conclusion on industrial applications of the models and tools

Throughout the industrial applications the models (Part 3) and the tools (Part 4) have been applied for visualisation and documentation of architectures, platforms, standard designs and product families. The models and tools are able to capture some of the central aspects of the standard designs and architectures.

The organ domain has proven to be useful for modelling the structures of standard designs and architectures. The formalism for modelling organ structures has been applied for modelling structures of standard designs and architectures. These models have been the key documentation of the standard designs and architectures in the design process as well as the final documentation of the projects. The tools have been applied with success in several projects.

The case from Bang & Olufsen has shown how to document standard designs. These were documented by means of organ models and a document describing the design rules. This documentation is essential as documentation of how to implement a standard design in a product.

Part 6

Conclusions and future research

The objective of this research has been to investigate the phenomenon of product families based on architectures. Part 6 concludes on the results of this research and suggests future research.

The topic of this research is product families based on architectures and standard designs. This research introduces a vocabulary for architectures along with two supporting tools.

The theoretical goal of this research has been to contribute to a theory for product families based on architectures. The contribution distinguishes and defines architecture, platform, standard design and design unit. The practical goal has been to develop tools and apply the tools in industrial projects. The industrial applications contribute to verification of the theoretical results.

Part 6 concludes the thesis. It contains a summary of the results, an evaluation of the research work as well as suggestions for further research.

21 Conclusion and evaluation of research contributions

The contribution to a vocabulary for product families based on architectures enables distinction among the phenomena: existing design unit, future design unit, existing standard design, future standard design, module, interface, architecture, assortment architecture, family architecture, product architecture, platform, assortment platform, family platform, product platform, architecture alignment and platform alignment. These concepts are proposed as a totality. This implies that the concepts are related to each other by means of theoretical and logic reasoning. The concepts extend the artefact theories Theory of technical systems and Theory of domains to be valid for product families.

21.1 Hypothesis no. 1 – Architecture

The first hypothesis states a building principle for product families exists. This building principle is denoted *architecture*. The hypothesis is repeated below (see also Page 21).

Hypothesis no. 1 – Architecture

It is possible to identify a model that is able to describe and document the building principle for individual products within a product family. This model, which is named “architecture”, consists of the following elements: design units, standard designs, interfaces and application characteristics. Designing within such an architecture enables re-use of building principles and standard designs.

Contributions

Throughout this research, it is shown that an architecture is a building principle for product families. The building principle describes some of the central elements of a product family. An architecture consists of design units, standard designs, interfaces and application characteristics.

The *standard designs* encapsulate the design entities that are re-used in several products or product families. The design units are the design entities, which are not re-used. The distinction between standard designs and design units is of importance as their nature is different. Standard designs have to be designed in such a way that they can be used in future products, whereas the design units only have the scope of one product. Consequently, the application aspects are different for standard designs and design units. A standard design requires a higher degree of documentation, higher degree of maintenance, appointment of responsibility, etc. than a design unit, in order to enable re-use in future products.

Standard designs and design units are either of the types future or existing. This distinction is introduced to enable an architecture to deal with the product variants currently under development and those being developed later on. It also enables a project team to make decisions on how to implement future standard designs and design units.

The interfaces, included in the concept of architecture, connect the standard designs and design units. These interfaces have to be developed and managed in agreement with the standard designs and design units. The consequence of unsuitable interfaces might be that standard designs have to be re-designed, or in the worst case that the standard designs cannot be re-used.

Another class of interfaces are those that connect the product to the surroundings, e.g. network, power supply, control signal, etc. The interfaces with the surroundings have to be designed and managed just as the interfaces among the standard designs and design units. These interfaces are of interest, because they are influenced by the customer and the customer's application. Changes in these interfaces might cause re-design, or in the worst case that the standard designs cannot be re-use.

Limitations of this research

One of the aspects, which needs further investigation is the understanding of how detailed an architecture should be. The “optimal” granularity of architectures and standard designs is often difficult to determine in industrial projects. An example: Should a microprocessor

be a standard design, or should the standard design include the microprocessor and its supporting circuits?

For application purposes it would be beneficial with guidelines on how to design an architecture? Also it would be beneficial to have guidelines on how to determine what is a good architecture?

One of the endless discussions that occurs in companies considering applying architectures is, "What degree of re-use should we aim for?". Some companies find it difficult to re-use physical standard designs due to industrial design. The concept of architecture and standard design suggests that the re-use does not have to be physically, it may also be re-use of PCB layouts, specifications, solution principles, etc. However, there is no doubt that physical re-use is desirable. It would be beneficial to investigate the re-use aspects further and identify the different classes of re-use.

One of the limitations of the concept of architecture and the modelling formalisms proposed in this research is their ability to visualise spatial interfaces. The applied approach only indicates that an interface exists between two standard designs or design units. The models do not visualise the spatial interfaces, which often are of importance for mechanical products as well as mechatronic products.

Conclusions

The concept of architecture has been meaningfully applied at several companies in several industrial projects. The concept of architecture has been applied in the industrial projects by means of modelling of their architectures. The visualisation and documentation of the architectures have enabled the companies to capture decisions related to the building principles of their product families. This has led to higher degrees of re-use than in previous projects. It is hereby concluded that hypothesis no. 1 is verified.

21.2 Hypothesis no. 2 – Standard design

One of the key elements of an architecture is the standard design. The second hypothesis deals with the understanding of standard design. The hypothesis is repeated below (see also 23).

Hypothesis no. 2 – Standard design

It is possible to describe re-usable solutions by means of three classes of characteristics - structural, functional and application characteristics. The re-usable solutions are denoted "standard designs". These three classes are necessary and sufficient for enabling re-use.

It is argued that a standard design is an encapsulation of organs into an entity that can be re-used in several products.

Contributions

This research argues that a standard design is an encapsulation of organs and parts that are designed to be used in several products or product families. A standard design can be described by its structural elements, functional properties and application characteristics. The structural characteristics are organs, parts and interfaces. Examples of functional properties are cost and performance. Application characteristics relate to responsibility, documenta-

tion, version control, etc. of the standard designs.

The tools and the industrial applications of standard designs suggest ways to document standard designs. One aspect is to document the structure of the standard design, i.e. its elements and their relations. Another aspect of documenting standard designs is to document the rules for implementation. These design rules focus on describing the interfaces, specifications, functionalities, etc. of the standard design.

This research proposes basic rules for when to appoint a design unit to be a standard design. These rules are proposed to emphasise the difference between standard designs and design units. The basic rules state that if a design unit should be appointed a standard design it has to be documented, designed to be re-used and someone in the R&D department must be appointed responsible for each of the standard designs.

Limitations of this research

Successful re-use of architectures and standard designs imply that the documentation exists and it is correct and up-to-date. This typically implies that the documentation has to be controlled by version, revisions, etc. Product Data Management systems (PDM-systems) are one of the means for this. However, this has not been within the scope of this research, but it is a key issue for successful re-use of standard designs.

The definitions of architecture and standard design have interfaces as a central element. One could argue that the interfaces should not be a part of both definitions, because it implies redundancy in the documentation. This research argues that the interfaces defined on architecture level are only defined in general terms. Whereas, interfaces defined as part of a standard design include the detailed documentation and specifications of the interfaces. A third approach would be to define the interfaces as an element that has equal status to a standard design. This would imply the interfaces in themselves have to be controlled and managed like a standard design, e.g. documented, appointed ownership, etc. Further studies of the interface phenomenon should bring clarity on these issues.

Concluding remarks

The industrial applications show that the concept of standard design is applicable for capturing design entities that are re-used. The applications also show examples of different types of visualisation and documentation of the standard designs. It is hereby concluded that hypothesis no. 2 is verified.

21.3 Tool for modelling variety

Product families including many variants can be difficult to comprehend. This research proposes a tool that can be applied for modelling the variety of a product family – the tool is called the *Product family master plan* (PFMP). The tool suggests that a product family can be modelled from three points of view. These are customer, engineering and part views.

Contributions

The customer view describes the product family from a customer's point of view. This implies describing the variety offered to the market. The engineering view describes the product from a functional point of view by means of organs. This implies describing the organ structure and the variety of organs. The part view describes the product family from a physi-

cal point of view. This implies describing the structure of bill of materials and describing the variety of assemblies and parts.

Causal links exist between the customer, engineering and part views. Reasoning can be done from the customer view to the engineering and part views. Features in the customer view are realised by one or more organs in the engineering view. The organs in the engineering view are realised by one or more parts in the part view. Reasoning can also be done from the part view to the engineering and customer views. Parts contribute to realisation of organs and organs contribute to realisation of features in the customer view. These causal links are important for making decisions on product families and architectures.

The PFMP has proven to be useful for modelling product families in three different types of projects. One type of project focuses on identification of variety in a product family, which does not add value to the customers. Experience shows that product families often include variety, which does not add value to the customers. These variants should be removed from the family. The second class of projects is those that aim at identifying engineering complexity. The causal links between customer and engineering views provide an indication of the complexity when developing customer specific variants. The third class of projects aim at creating consensus between Sales, Engineering and Production. A PFMP forms a professional tool for a dialogue between Sales, Engineering and Production.

Limitations of this research

Experience from industrial applications of PFMP reveals that it is difficult for companies to determine the “goodness” of a product family. The linking of the three views contributes to one way of reasoning on the goodness of a product family. But other aspects are just as important. Examples of such aspects are: What products contribute to a profitable business, what variants add value to the customers and what product variants are essential for the business from a strategic point of view? These are some of the questions that are not covered by the application of the PFMP tool.

Keeping a PFMP up-to-date, as a product family evolves over the years, is challenging for many of the companies. New commercial variants, new components, updated components, etc. are typically added to a product family on a daily or monthly basis. This implies that the PFMP has to be continually updated. The approach for this has been to manually update the PFMP. However, this can be an overwhelming task. To ease the maintenance task, the PFMP should be an integrated part of an Engineering Changes Notification System (ECN-system), Enterprise Resource Planning System (ERP-system) or Product Data Management System (PDM-system). The ECN-system would enable the PFMP to be subject to version control, revision control, etc. Integration with the ERP- or the PDM-system would automatically update the PFMP.

Concluding remarks

Based on the industrial applications it is concluded that the PFMP is a powerful tool for modelling the variety of product families. It enables modelling of a product family's variety from customer, engineering and part points of view.

21.4 Evaluation of results

This research has sought to balance the development of insight in the phenomena and ap-

plication of the findings. The dialogues with the industry have provided important inspiration for the theoretical work. The originality of the results of this research lies in:

- A sharp distinction between design entities that are re-use and those that are not re-used, i.e. standard design vs. design unit.
- A distinction between architecture and platform. An architecture is the building principle for product families. A platform is the physical and re-usable realisation of the architecture.
- Extensive verification of the theory contributions, models and tools in industrial projects.

22 Future research

The goal of this research is to contribute to a theory of product families based on architectures. As insight into the phenomena is obtained in this research project, but new questions arise. Some of the questions could be objects for future research.

It is emphasised in this research as well as in the literature that interfaces are essential. New insight into this phenomenon would be beneficial. This insight should explain the different classes and characteristics of interfaces. Such insight could ease the modelling and management of interfaces.

Experiences from industrial applications reveal that visualisation of architectures and standard designs are important for capturing the essence of architecture and standard design and for communication of the decisions. The primary visualisation tools applied in this research and in the literature are based on block diagrams, but other tools and models are desired.

One of the aspects that needs further investigation, is the mapping of a product family to the markets. New insight and modelling formalism are desired. Likewise, the mapping of a product family to the production capacity needs further investigation. These two aspects are essential for evaluation of the “goodness” of architectures and the standard designs.

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Appendix 1. Publications within this research

Harlou, U. "*DFM af temperaturføler hos Bang & Olufsen*", [In Danish], Department of Mechanical Engineering, Technical University of Denmark, 2000.
Report: 74 pages

Harlou, U. "*Familieskab imellem B&O's højtalerfamilier*", [In Danish], Department of Mechanical Engineering, Technical University of Denmark, 2000
Report: 52 pages

Harlou, U. "*Product Family Master Plan as Basis for Product Modeling and Engineering Design*", Fuglsø, Denmark, 2000.
Conference paper: 18 pages

Harlou, U. "*On the Way Towards Definition of Product Architecture*"
Symposium DFX 11th & 12th of October 2001, Erlangen, Germany.
Conference paper: 14 pages

Hansen, P.H. andreasen, M.M., Mortensen, N.H., Harlou, U. and Jensen, T. "*Managing Modularization*" EIASM, The 8th International Product Development Management Conference, Twente University, Enschede, The Netherlands, 2001.
Conference paper: 11 pages

Hansen, P.H. andreasen, M.M., Harlou, U., Gubi, E. and Mortensen, N.H. "*Understanding the Phenomenon of Modularization*" International Design Conference, Design 2002, Dubrovnik, Croatia, May 14 - 17, 2002.
Conference paper: 5 pages

Harlou, U. "*Documenting standard designs*" Department of Mechanical Engineering, Technical University of Denmark, 2004.
Report: 12 pages

Harlou, U. "*Bang & Olufsen case: Reducing R&D-resources by means of re-use*" Department of Mechanical Engineering, Technical University of Denmark, 2004.
Report: 17 pages

Andreasen, M.M., Mortensen N.M. and Harlou, U. "*Multi Product Development: New models and concepts*" 15. Symposium DFX, Neukirchen, Germany, 14th & 15th October 2004.
Conference paper: 11 pages

Mortensen, N.H. and Harlou, U. "*Multi Product Development*", Chapter in "*Handbuch für Produktentwicklung*", B.Schäppi Springer Verlag, Germany, 2005. Chapter in book: 33 pages

Mortensen N.M., Harlou, U. and Andreasen, M.M. "*Identification of platform levels*" ICED 2005, Melbourne, Australia, 2005.
Conference paper: 11 pages